

# Chapter 4 CAUSES AND MECHANISMS OF FISH DOWNSTREAM MIGRATION FROM RESERVOIRS WITH A SLOW WATER EXCHANGE

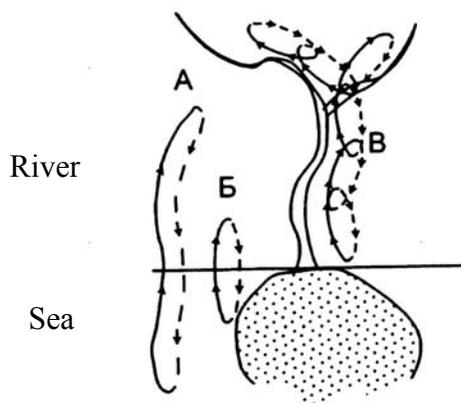
Downstream migration of juvenile fishes is an adaptation aimed at finding habitat and new areas for feeding, thereby expanding the feeding areas of the species. Downstream migration is an important part of the fish life cycle and an inseparable part of their migration ring (Fig. 4.1). Downstream migration, to a large extent, affects further life of the fish populations, i.e., their number, as well as the scope and character of migration in the consequent periods of life (Nikolsky, 1974; Pavlov et al., 1981; Pavlov, 1994).

Various fish species have various migration features that correspond to their relationship with the environment. This relationship will be different in limnic and lotic types of reservoirs. The major differences that affect fish migration in lakes and manmade reservoirs will be a slow water exchange and the characteristics of the water intake currents. Before we discuss how these features affect downstream migration, we need to discuss the general theory of downstream migration mechanisms.

## 4.1 General Theoretical Aspects of Mechanisms of Downstream Migration of Young Fishes

On studying the causes of fish migrations, it is very important to distinguish the historical causes (relevant to the entire period of the species historical development) and the current factors that make the migrations happen now. The identification of the “actual” reasons of the migration is related to finding their adaptive significance (Vasnetsov, 1953; Mantejfel', 1959). Therefore, all direct cause-and-effect relationships that result in the migrations should be defined as the mechanism of the migrations, while the general tendency of the migrations should be interpreted as the historical reason that, in the process of the natural selection, has resulted in the migrations (Pavlov, 1979).

We have already described a wide range of cause-and-effect relationships that affect fish downstream migrations (Pavlov, 1979; Pavlov et al., 1981, 1988, 1991a; Pavlov, 1994). The general theoretical assumptions described below are mostly based on the studies of the rivers and, to a lesser extent, on the studies of manmade reservoirs and lakes.



**Figure 4.1 Migration rings of diadromous (A), amphidromous (B) and resident fishes (B)**

Mechanisms of various levels can be identified in the downstream migrations of young fishes. The mechanisms of the first level create the precursors of migrations; the mechanisms of the second level implement the migration, while the mechanisms of the third level determine the spatial and temporary structure of distribution of the migratory fishes.

**Mechanisms of the first level.** These mechanisms include the inherent behavioral reactions and morphological features that affect the spatial distribution of the juvenile fishes and stimulate their downstream migration. To make the downstream migration happen, a fish needs to find itself in a water flow. This condition will be brought about by a pelagic distribution of the fish species in both rivers and manmade reservoirs. Their pelagic distribution will be provided by the three directions of adaptations, i.e., morphological and two behavioral directions, with the latter being presented by both non-specific and specific reactions.

Regarding *morphology*, the adaptations are aimed at reducing the specific weight and generating positive buoyancy of the organisms: hydration of eggs, incorporation of fat into the eggs and the yolk sac of the prolarvae, the presence of the swim bladder and the ability of older fish to regulate its volume.

*Non-specific inherent behavioral reactions* are not related to the presence of currents. These are “candle”-type vertical movements to lift the brood from the bottom to the water mass, positive photoreaction, negative thigmotaxis, preference of hidden areas with a small number of the visual markers and, therefore, avoidance of the littoral vegetation and rugged terrain. The adaptive significance of these reactions has a number of functions. They are related but not limited to respiration, finding habitat after spawning, and protection from predators. With the presence of currents, they will result in downstream migration.

*Specific behavioral reactions* are associated with the presence of currents. They result in intensification of swimming activity and the orientation of swimming towards the current. The intensification of swimming activity, even with sporadic transitions, will increase their chances of being in the transit flow, while the orientation directs the fish towards the current. These reactions are motivated and they are related to certain physiological (migration) “mood” of the

juvenile fishes. This “mood” has been proved not only for anadromous fishes, but also, according to the latest data, for the resident fishes, e.g., for roach (Pavlov et al., 1998).

Non-specific and specific behavioral reactions are those reactions that have been defined in our previous publications (Pavlov, 1979; Pavlov et al., 1981) as active elements of downstream migration of juvenile fishes.

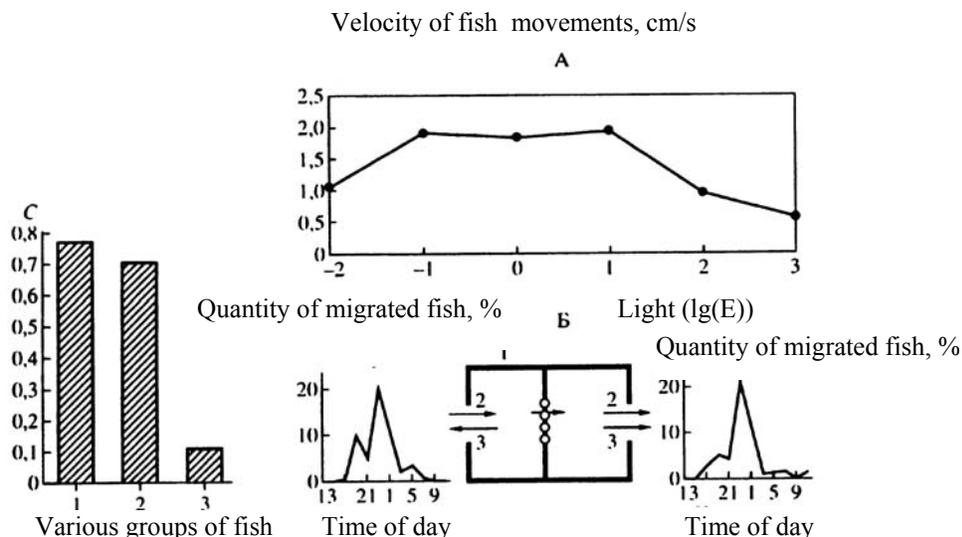
The fishes that do not perform downstream migrations have the opposite morphological and behavioral adaptations that keep them away from the currents. Specifically, their rheotaxis helps them resist the current; negative photoreaction makes them go to the bottom, and negative buoyancy, i.e., the presence of the suction cups and elongated pectoral fins, keep them near the bottom. They prefer littoral vegetation and rugged terrain, and avoid areas with few visual markers, thereby making it easier to avoid strong currents and settle down in the littoral areas with weak currents or without currents. All these adaptations are primarily aimed at keeping the fishes away from the currents.

To a very large extent, a range of behavioral and morphological adaptations depends on the species and age of the fish, and, consequently, the mechanisms of the first level depend on these factors. As an example, we would like to describe the relationship between these adaptations and the downstream migration on one of the best-studied species, i.e., roach.

The roach is a typical representative of phytophilous species; it lays sticky eggs in the littoral vegetation. Its prolarvae (Phase A) have special glands responsible for attachment to the vegetation, and, therefore, the roach migration at this lifestage is accidental. When the swim bladder is being filled (Phase B), the prolarvae have a positive photoreaction and perform “candle”-type vertical movements from the bottom upward for taking the air (Pavlov et al., 1981). At that time, the beginning of their intense downstream migration in the rivers and the absence of migration in the reservoirs have also been observed. The latter can be explained by the fact that the roach spawning areas are located far away from the water intake currents and their prolarvae, as a rule, are not present in the pelagic zones of the reservoirs where these currents are especially strong.

The roach larvae also have a positive photoreaction, but they prefer to inhabit the water mass. They stay in the littoral zone with weak currents or without currents in the daytime. In the evening and at night, a significant number of the roach larvae can be found in the river flow, migrating with the current. The remaining individuals remain in the littoral zone, forming rheo- and limno-conglomerations (Nezdoly, Kirillov, 1997). The roach species from the rheo-conglomerations prefer the river areas with a weak current, while the roach from the limno-conglomerations prefer the areas without currents. The migrants are bigger than the littoral fish (Pavlov et al., 1990) and have a strong positive photoreaction (Legky, Pavlov, 1987). According to the latest data (Pavlov et al., 1998), the migratory fish have a higher hormonal status (11 substances from the four hormonal systems) than the littoral fish. The fish from the rheo-conglomerations are close to the migratory fish regarding the hormonal status, while the fish from the limno-conglomerations have a much lower hormonal status (Fig. 4.2). It is interesting that the roach larvae have specific current-induced behavioral reactions in the evening, i.e., they become more active and directions of their migrations become better defined (Pavlov et al.,

1997). When the light goes down, most larvae go towards the current from the experimental chambers through the holes in those chambers. They leave the chambers both with the current and against the current, and the velocity of their movements goes up (Fig. 4.3).

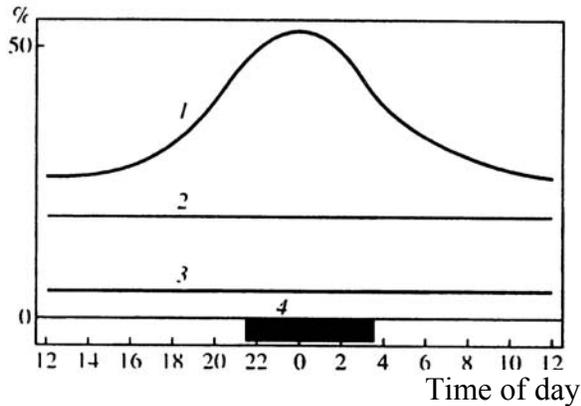


**Figure 4.2** Hormonal status of migratory fish (1), fish from rheo-conglomerations (2) and limno-conglomerations (3).

**Figure 4.3** Migration dynamics of roach larvae at Phases C1 – D1 (ref.: Pavlov et al., 1997)

A – speed of fish migration in a hydrodynamic experimental chamber; Б – daily dynamics of larvae leaving the chamber; 1 – experimental chamber; 2 – direction of current; 3 – directions of fish migrations

The fry do not react positively to light; they stay near the bottom and in the vegetation areas. Their tactile mechanism of orientation starts functioning in the flow. Their migration in small rivers drastically slows down and gradually stops. In large rivers, one of the amphidromous roach subspecies, i.e., Caspian roach (*Rutilus rutilus caspicus* Jak.) continues migrating during the juvenile period of development (Pavlov et al., 1966). At night (when the light decreases), the Caspian roach fry leave the littoral zone for the transit flow, and most of the fry change from negative buoyancy to positive (Fig. 4.4). However, the European perch fry that do not perform downstream migration in the rivers have the same negative buoyancy during 24 hours. Non-migratory fish species, i.e., rudd, do not experience any change in their buoyancy, and the rudd fry go to the waterline at twilight. It is obvious that the positive buoyancy of the migratory fry is associated with their distribution near the water surface, stimulating the downstream migrations, while the non-migratory fish tend to always have negative buoyancy to prevent migration from their habitat.



**Figure 4.4** Fish with negative buoyancy in the Volga River delta littoral zone at various times of the day (ref.: Pavlov et al., 1997)

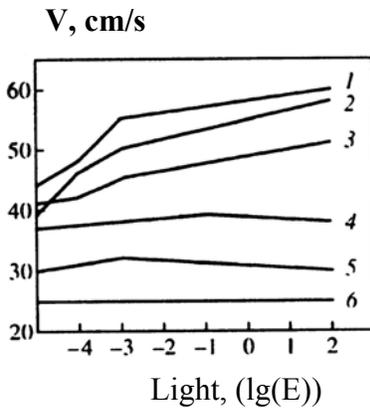
1 – Caspian roach; 2 – rudd; 3 – European perch; 4 – darkness

In the reservoirs, due to the specific behavioral reactions, the roach fry periodically leave the littoral and sublittoral zones for the pelagic zone. The roach fry downstream migration has been observed only during those periods of time (Kostin et al., 1997).

This example, as well as the studies of the downstream migration for other fish species (Pavlov et al., 1981), shows that morphological adaptations are the most common for eggs and prolarvae, non-specific behavioral reactions can most frequently be observed with prolarvae and early larvae, while specific behavioral reactions can be observed with early larvae, but they are the most typical for the late stages of the juvenile fish development.

**Mechanisms of the second level** stimulate downstream migration of the juvenile fishes, resulting from their distribution and the presence of currents. It is interesting to know that the downstream migration in this case is made possible due to rheotaxis (Lyon, 1904; Arnold, 1974; Pavlov, 1979) Rheotaxis is an inherent compensation movement against the current. It prevents the fish from being drifted with the current. To understand the downstream migration mechanisms, it is important to know how “neutralization” of the rheotaxis occurs. Therefore, we would like to briefly describe how the rheotaxis that has locomotive and orientative behavioral components works.

The locomotive activity of fish in the flow has several functional characteristics, such as the threshold velocity, i.e., the minimum water flow velocity when the fish start swimming against the current; critical velocity, i.e., the minimum current velocity when the fish begins drifting with the current; swimming capability, i.e., how long the fish can swim at a certain current velocity. As a rule, the bottom fish have critical velocities that are a factor of two or three lower than those of the fish inhabiting the water mass or the water surface (Fig. 4.5). One of the mechanisms of rheotaxis neutralization is to be in the water flow area where the current velocity exceeds the critical velocity.



**Figure 4.5 Critical current velocity as a function of light for various fish species (size 50 – 65 mm) (ref.: Pavlov, 1979)**

1 – European perch; 2 – rudd; 3 – roach; 4 gobies; 5 – Russian sturgeon (*Acipenser guldenstadtii*) (70 – 75 mm); 6 – sturgeon

The fry can find their way in the flow by vision or touch (Lyon, 1905; Dijkgraaf, 1933; Pavlov, Pakhorukov, 1983), lateral line organs (Dijkgraaf, 1962) and labyrinth (Gray, 1937; Harden Jones, 1968). Vision has the key role for orientation for the fry of most species, while a sense of touch can be the most important for some bottom fish (*Acipenseridae* sp.) (Pavlov, 1970). The lateral line organs and labyrinth provide orientation in turbulent flows with the current gradients (Pavlov, 1979; Pavlov et al., 1982; Pavlov, Tyrukov, 1988).

The opto-motor reaction that makes the fish follow visual markers is considered to be a visual mechanism of rheotaxis (Pavlov, 1979; Arnold, 1974). The fish orientation changes in the process of ontogenesis. For example, vision is considered to be the leading orientation mechanism for the osseous juvenile species. As soon as the light goes below the threshold values for the opto-motor reaction, the early brood (below 30 mm) is immediately drifted with the current. The threshold light values vary for various types of young fishes (Fig. 4.6).

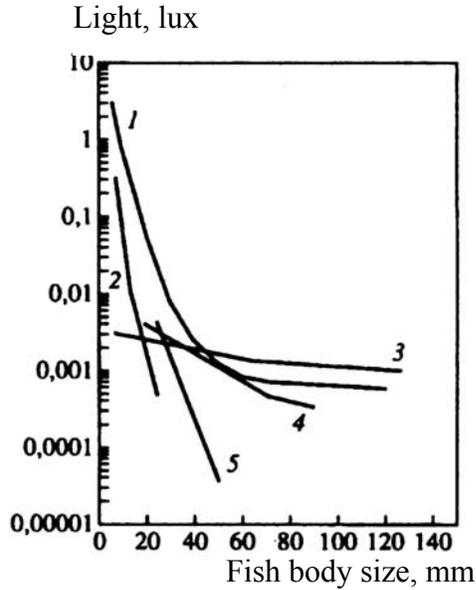


Figure 4.6 Light threshold values as a function of body size for evaluation of the opto-motor reaction of young fishes (ref.: Pavlov, 1970).

1 - Caspian roach; 2 – carp; 3 – bleak; 4 – ruffe; 5 – carp bream

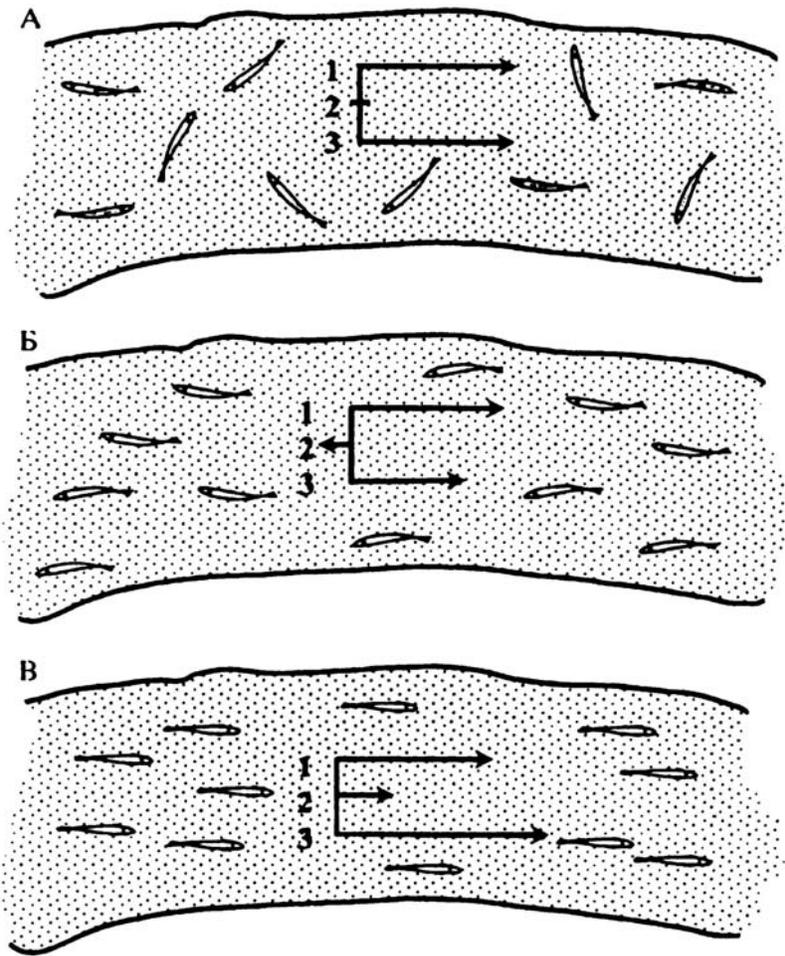
Locomotive and orientation components of rheotaxis are the two sides of the same phenomenon. Therefore, the rheotaxis will be immediately affected by any adverse change in orientation or locomotive capabilities.

It also should be noted that rheotaxis is expected only in a homogeneous flow. In case of rheogradient conditions that are more likely to happen naturally, the fish reaction to the current and the fish distribution in the flow appear to be entirely different. The fish either select certain velocity zones in the rheogradient, or avoid the current, going to shelter, littoral zone or coves. The latter prevents downstream migration.

Rheotaxis (locomotive activity) can either be weakened by certain physiological conditions of fish, slowed down or even suppressed by other, stronger, behavioral reactions.

The types of downstream migration vary, depending on how the fish migrates with the current (Fig. 4.7), specifically: passive migration, i.e., drifting with the current without orientation in the flow; active migration, i.e., active swimming with the flow; and active – passive migration, i.e., trying to swim against the current, but being drifted with the current. Various forms of downstream migration have their own mechanisms (rheotaxis “neutralization”).

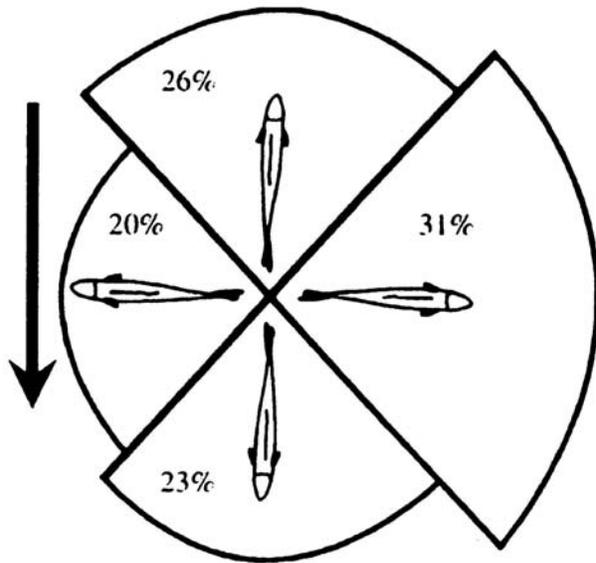
*Passive* migration is either associated with a physical inability to resist the flow due to exceeding the critical velocity (prolarvae and early larvae), or lack of their orientation (larvae and early fry) against the current (visual orientation due to decrease of light or murky waters, and a loss of tactile orientation due to leaving the bottom). If the water is clear, passive migration only occurs at night or in the dark.



**Figure 4.7 Orientation and velocity of various forms of downstream migration**

Forms: A – passive, Б – active – passive, Б – active; 1 – current velocity; 2 – velocity of fish movements, 3 – fish downstream migration velocity (total)

It should be noted that the term “passive migration” only reflects how fish move with the current. It means that the migratory fish can be oriented in any direction (Fig. 4.8) and its migration velocity is practically equal to the current velocity. It does not mean that the fish species are entirely passive and do not have any reactions. They maintain dorso-ventral body position, have photoreaction and compensating hydrostatic reaction, and they also react on the change of the current velocity (Pavlov, Shtaff, 1981) and various hydrodynamic stimuli (Pavlov, Turukov, 1986). In the latter case, the young fishes can even restore their orientation against the current for a certain period of time and have rheotaxis. Therefore, it does not seem acceptable to compare the young fish migration with the downstream movements of soil particles (Nusenbaum, 1971), or develop fish migration models, imitating migration of confetti, sawdust or any other floating objects (Glejzer, 1978).



**Figure 4.8 Orientation of roach larvae during downstream migration in the Bolshaya Kosha River in 1996**

Arrow – direction of current

*Active – passive* migration takes place with a drastic decrease of swimming capability of fishes due to certain factors, such as lack of food, low water temperature or water contamination, etc. However, the orientation of the species against the current remains, and the migration velocity is equal or slightly less than the current velocity. With this type of downstream migration, unlike the passive migration, the loco-motor component of rheotaxis decreases, but its orientation components remains the same.

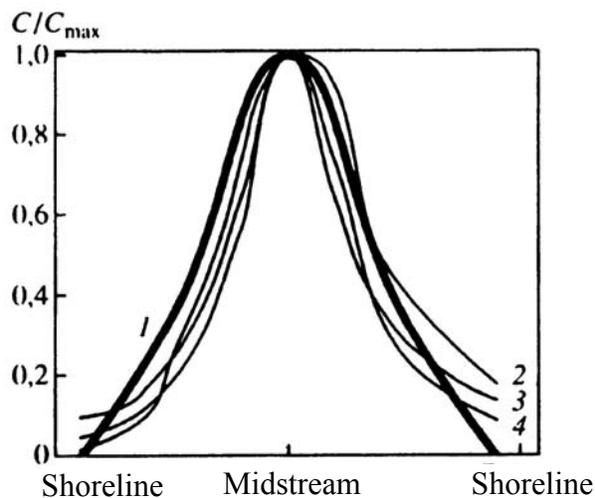
There is no rheotaxis with the *active* downstream migration because it is replaced by other reactions. The velocity of fish exceeds the current velocity. The fish usually migrate in the daytime and during later phases of life (fry and older).

Stable abiotic factors (light and transparency of water) make passive migrations happen and, consequently, the passive migrations cannot be avoided. Under these circumstances, the historical cause for downstream migration, i.e., lack of food in spawning area, cannot be considered the major reason for such migration. Passive downstream migration is typical for prolarvae, larvae and young fry.

Active and active – passive migrations are more variable and they are frequently connected with the variable biotic factors of the environment, i.e., density of fish population, territorial and aggressive behavior of species and, especially, availability of food. Therefore, these migrations do not depend on time and can be characteristic of various migratory fish, depending on the specific conditions in the river and age of fish (Salmonidae – 1- 5 years old, Acipenseridae – 0.3 – 5 years old, and *Vimba vimba* – 0.3 – 3 years). It should be noted that these types of migrations, especially the migration of anadromous fishes, are affected by the migration “mood” or status of fish, for example, during smoltification. In this case, the rheotaxis goes down and, regardless of any above-mentioned factors, downstream migration cannot be avoided.

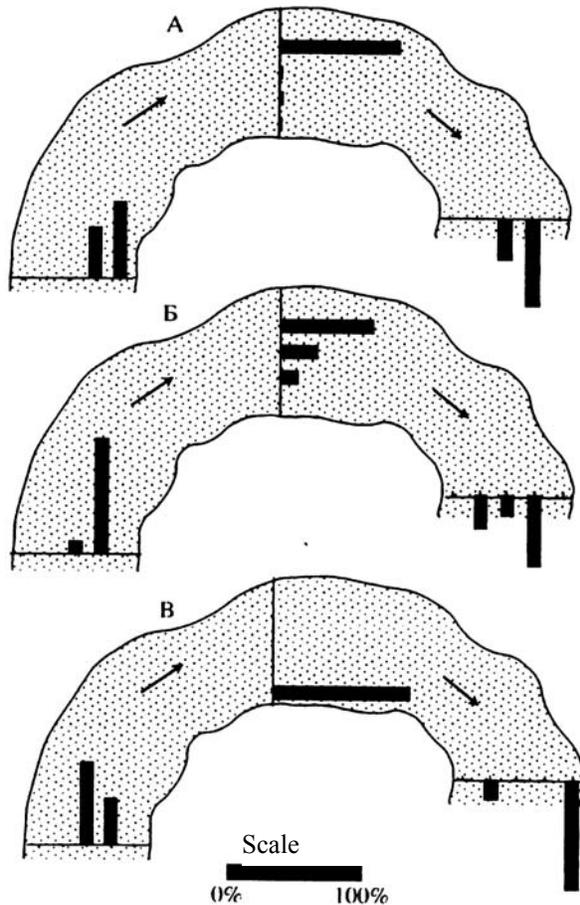
**Mechanisms of the third level** create the spatial distribution of the migratory fish, and they can be physical or biological. The physical mechanisms are of a hydrodynamic nature and they are related to various currents inside the major flow. In rivers, these currents are associated with transverse circulation and whirlpools of various sizes, resulting from turbulence and rheogradients. In lakes and manmade reservoirs, these are circulation currents generated by wind and convection and, to a large extent, they most frequently occur in the water mass interface and near the shoreline. Biological mechanisms are mostly associated with various behavioral reactions, resulting from various environmental factors. These are as follows: photoreaction, hydrostatic reaction, preference in the rheogradient, temperature preference, and avoidance of contaminated or low oxygen areas, as well as the food or defense-oriented reactions.

*Horizontal* distribution of the passive migrants in the river primarily results from physical mechanisms, specifically, a turbulent mixing of the flow. Spiking the water with radioactive isotopes in the lower Volga region and the comparison of these results with the migratory juvenile fish concentration distribution in various areas of the river has shown that they were identical (Fig. 4.9). It means that the physical mechanisms are very important for the horizontal distribution of migratory fish (Pavlov et al., 1995).



**Figure 4.9 Distribution of migratory fish relative concentration and concentration of radioactive isotopes in the river (Pavlov et al., 1994)**

Concentration: 1 – isotopes, 2 – Percidae; 3 – Cyprinidae; 4 – Clupeidae



**Figure 4.10 Redistribution of Cyprinidae larvae (16 – 20 mm long) in the river bend (% of the total concentration)**

A – surface; B – water mass; B – bottom (ref.: Pavlov et al., 1982)

Vertical distribution of migratory fish, unlike horizontal distribution, depends on both physical and biological mechanisms. First of all, it results from varying buoyancy of juvenile fishes (Pavlov et al., 1997a). There are more migrants with positive buoyancy near the surface, and there are more migrants with negative buoyancy near the bottom. But it appears that the situation may be just the reverse, i.e., there may be migratory fish with positive buoyancy near the bottom and with negative buoyancy near the surface. Our studies show that it may result from transfer of fish by turbulent vertical flows (Taradina et al., 1997).

Another illustration of these mechanisms is the fish distribution in the river bends where the young migratory fish concentration is being redistributed towards the concave shore (Fig. 4.10). On the one hand, it depends on the physical mechanisms, specifically, transverse circulation of the flow and its turbulence, and, on the other hand, it depends on the biological mechanisms, i.e., positive photoreaction, positive buoyancy and a compensating hydrostatic reaction that keep most fishes near the surface (Pavlov et al., 1982).

Similar combinations of physical and biological mechanisms can be observed in the reservoirs. Circulation currents, resulting from thermal stratification and wind exposure, often occur in the

littoral zones of the reservoirs with a slow water exchange. In those zones, spatial redistribution of larvae and fry (Gorin, 1991) depends on their daily vertical movements that are affected by their positive photoreaction and change of buoyancy from positive (daytime) to negative (night). In the daytime, the juvenile fish drift in the surface water with the wind currents, thereby accumulating in the littoral zone. At night, they go deeper and scatter throughout the areas of the circulation currents.

Spatial distribution of migratory fish in the open part of the reservoirs also depends on a combination of various mechanisms. On the one hand, there are physical mechanisms, specifically, surface wind currents and deep circulation currents (Konobeeva et al., 1980; Konobeeva, 1983a). On the other hand, there are vertical daily movements of juvenile fish associated with food and defense-oriented reactions, photoreaction, hydrostatic reactions, and other biological mechanisms.

Therefore, the first two out of the three described levels of downstream migration appear to be the most important because they actually initiate the downstream migration. The mechanisms of the third level do not generate the downstream migration, but they only adjust the spatial distribution of the migratory fish. The studies show that the biological mechanisms of downstream migration will not significantly differ in limnic and lotic types of reservoirs. However, the downstream migration mechanisms will work differently in lakes and manmade reservoirs, in comparison with rivers, due to the hydraulic structure of the flow in the reservoirs with slow water exchange.

The currents vary in the littoral and bathyal zones of the reservoirs, and the velocity vector in the reservoir changes with time both in value and in direction. Usually this vector is shorter than in the rivers. It may modify the mechanisms of the first and second levels, responsible for the downstream migration.

Currents in the pelagic zone of the reservoirs are mostly generated by movements of the water mass, resulting from water intake, presence of tributaries, wind and other currents, and temperature convergence, etc. The combination of various factors that form various currents may result in the fact that the reservoirs may have multiple currents with various directions and velocities. Both current velocities and directions are not stable and are subject to change, depending on the presence of various factors. The most stable is the water intake current that is considered to be the driving force of the downstream migration. It is with the water intake current that the described earlier mechanisms of the three levels work. Its major difference from the river flow is that it has a lower velocity.

On approaching the water intake zone, the water intake current velocity increases. There, the current velocity vector may change its direction, deviating from the horizontal direction and creating upwelling and downwelling currents, due to the location of the HPP gatewell. All these factors affect the fish downstream migration from the reservoirs.

Taking into account various conditions for downstream migration mechanisms in various zones and areas of the reservoirs, the process of formation of fish downstream migration should be divided into the following stages: fish entrainment in the water intake zone, fish migration

through the water intake zone and fish migration into the HPP tailwaters. Below is the description of how the mechanisms of the three levels affect the fish migration in these stages.

## 4.2 Fish Entrainment in the Water Intake Zone

In the water intake zone, the juvenile fish is exposed to the water intake current and, therefore, its downstream migration becomes very likely. All fish migration routes go through this area of the reservoir. Therefore, the water intake zone is very important for downstream migration. Let us consider how the fish gets entrained in the water intake zone and what mechanisms stimulate this process.

The fish can get entrained in the water intake zone if one of the following three conditions takes place: 1) hatching in the vicinity of the water intake zone; 2) active swimming; 3) passive drifting with the water intake current.

*Hatching* in the vicinity of the water intake zone can only be possible if the fish spawns there. Downstream migration is possible when the prolarvae get loose from the substrate and go upward. Since their swimming capability is not developed, they cannot resist the water intake current and, therefore, all of them are likely to migrate through the HPP. Since the water intake zone is small enough and the prolarvae development period is not very long, this type of migration does not take a long time and is not significant.

*Active swimming* in the reservoirs is characteristic of adult fish and young fishes of diadromous and amphidromous fishes. Regarding resident fishes, active migration (migration in the littoral and bathyal zones) has been observed for very few species, e.g., fry and brood of pikeperch (Gorodnichij, 1978; Pavlov et al., 1981, 1988). Such migration will occur only if there is a lack of food. In this case, the migration will be of mass nature, but it will not last a long time. Therefore, in most cases, active migration of the young resident fishes does not seem to explain the general tendencies of their downstream migration from the reservoirs.

Most resident fishes get entrained in the water intake zone due to *passive migration* with the water intake current. Therefore, we'll mostly describe this type of migration.

This migration primarily occurs in the pelagic zone of the reservoirs and, therefore, it will be more characteristic of the fishes that inhabit the pelagic zone. This fact has been confirmed by the studies of a number of reservoirs. For example, it has been observed that the fish species that inhabit the littoral zone of the Ivan'kovskoe reservoir primarily migrate when they go to the pelagic zone (Kostin et al., 1997). The time of their migration matches very well the time of their presence in the pelagic zone (Table 4-1.).

**Table 4-1 Presence of juvenile fishes in pelagic zone of the reservoir (1992) and the time of their migration through Ivan’kovskaya HPP (1989 – 1990)**

Species	Phase of ontogenesis	Time of presence in the pelagic zone (decade of the month)		Time of downstream migration through HPP (decade of the month)	
		beginning	end	beginning	end
Pikeperch	C <sub>1</sub> – M	(1) June	(3) August	(1) June	(1) September
European perch	D <sub>1</sub> – M	(1) June	(1) July	(1) June	(3) June
	M	(2) August	(1) September	August	(3) August
Carp bream	C <sub>2</sub> – D <sub>1</sub>	(2) June	(3) June	(1) June	(1) June
		(2) July	(3) July	(3) June	(3) July
		(2) August	(3) September	(2) August	(1) October
Roach	M	(2) July	(3) July	(2) July	(3) July
	M	(3) August	(1) September	(3) August	(1) September
Bleak	C <sub>1</sub> – E	June	June	June	June
	M	August	(1) September	July	(1) August

Note. M – Fry older than F phase.

Similar results have been obtained for Sheksninskoe reservoir where simultaneous studies of fish distribution and fish downstream migration have been performed. As it has been found out, the pikeperch downstream migration has been observed only when pikeperch were present in the pelagic zone (Fig. 4.11). Roach and carp bream that mostly inhabit the littoral and sublittoral zones migrate only when they are present in the pelagic zone of the reservoir.

Migration of young fishes to the pelagic zone results from the mechanisms of the first and second levels.

In both rivers and reservoirs, the mechanisms of the first level have three directions of adaptations. The morphological adaptations of fishes do not differ in limnic and lotic types of reservoirs. Non-specific behavioral reactions are not as important in the reservoirs as they are in rivers because their influence on the downstream migration primarily depends on the hydraulic conditions and, since they vary in various ecological zones, these reactions will depend on where the fish is located.

Specifically, if the fish goes up from the bottom of the pelagic and sublittoral ecological zones, they almost always wind up in the pelagic zone. In the littoral zone, their downstream migration will depend on the resulting vector of the current velocity. The value and direction of this vector primarily depends on the wind, convection and other time-variable phenomena. Therefore, the juvenile fish migration from the littoral to the pelagic zone of the reservoir, resulting from these currents and non-specific reactions of the migrants, will be less stable than in the rivers.

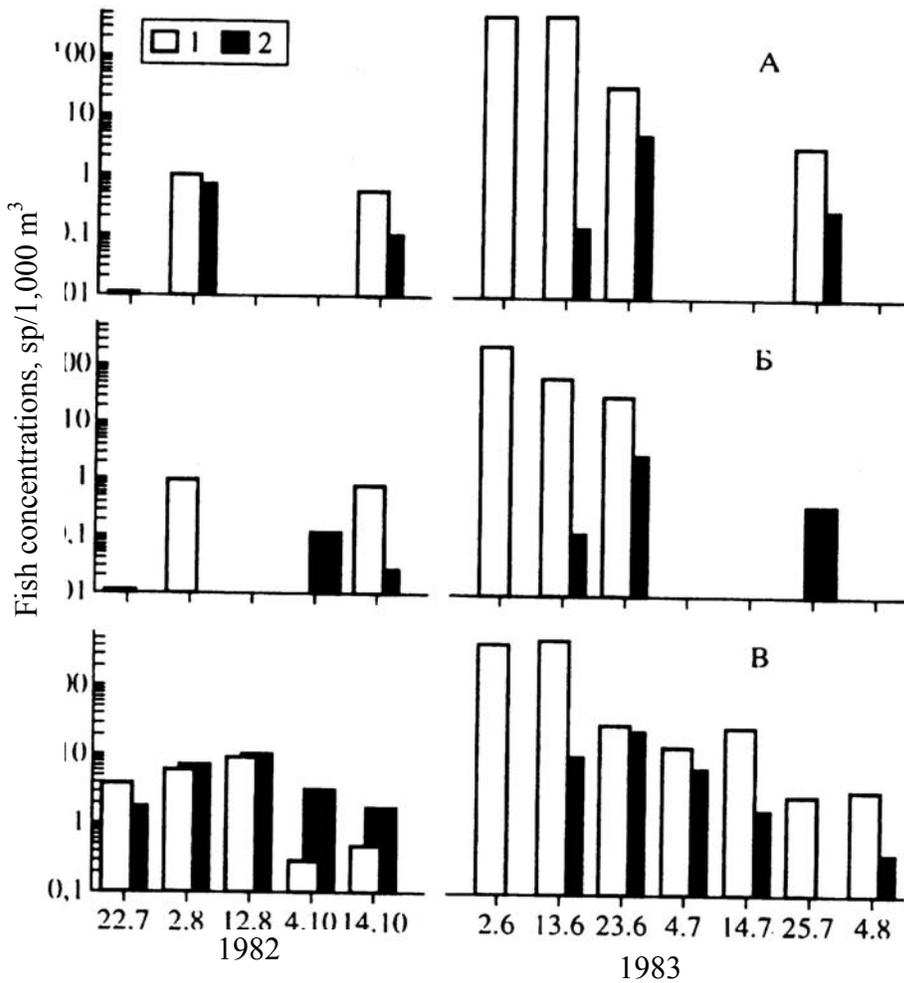


Figure 4.11 Concentration of inhabitants of the dam area (1) and migrants (2) from Sheksninskoe reservoir during the days of simultaneous observations

A – roach; Б – carp bream; B – pikeperch

Reactions associated with feeding patterns of the fish when they feed on plankton can also be considered non-specific reactions that affect movement of the young fish from the littoral zones of the reservoirs to the pelagic zones. The variety and concentration of plankton vary within the vegetation, and the pelagic zone sometimes seems to have a better variety. Therefore, the young fishes perform feeding migrations to the pelagic zones during certain periods of ontogenesis. The primary feeding goal of those migrations has been confirmed by the fact that Cyprinidae larvae appear to be better fed in the pelagic zone (30 – 40 meters from the shore) than near the shoreline (Mikheev, 1985). Similar data have been obtained for carp fry (Bohl, 1980). Beyond that, our studies of the Ivan'kovskoe reservoirs have shown that young roach and carp bream go to the pelagic zone from the littoral zone because they can find zooplankton there to feed on (Fig. 4.12).

It is not quite clear yet how specific behavioral reactions affect the migration of the fish species to the pelagic zones of lakes and manmade reservoirs. However, it is known that the current velocities that generate those reactions are compatible with the current velocities in the littoral zones of the rivers. Therefore, we may assume that young fishes that inhabit reservoirs with a slow water exchange also have specific behavioral reactions, thereby initiating the mechanisms of the first level with their migration to the pelagic zone of the reservoir.

The mechanisms of the *second* level in both rivers and reservoirs with a slow water exchange depend on the ways of rheotaxis “neutralization”. Neutralization means that the critical current velocity increases with the existing conditions of the orientation. The absence of conditions for orientation in the pelagic zone initiates the mechanisms of the second level. Such way of “neutralization” of rheotaxis primarily generates downstream migration in the pelagic zone. The conditions for visual and rheogradient orientation there are very limited even in the daytime. The current velocity gradients are not related to immobile objects, but they are affected by mixing of the water mass, resulting from interactions of various currents. Therefore, immobile markers in the pelagic zone are not likely to be used for orientation. Consequently, we can assume that downstream migration there will be passive for most fish migrants.

The operation of mechanisms of the *third* level in reservoirs significantly differs from that in rivers. In the rivers, the fish migrates primarily in the evening and at night, and in the daytime it either slows down or stops. In reservoirs, young fishes are present in the pelagic zone both in the daytime and at night and, consequently, their migration goes on continuously. It can be explained by the mechanisms of the second level. In reservoirs with a slow water exchange, wind and compensating currents, together with vertical daily movements, affect the fish distribution (Podubny, 1971; Konobeeva, Podubny, 1982; Konobeeva, 1983a). Those currents may significantly affect the migration speed in the pelagic zone towards the water intake zone, and they also may change the direction of the migration.

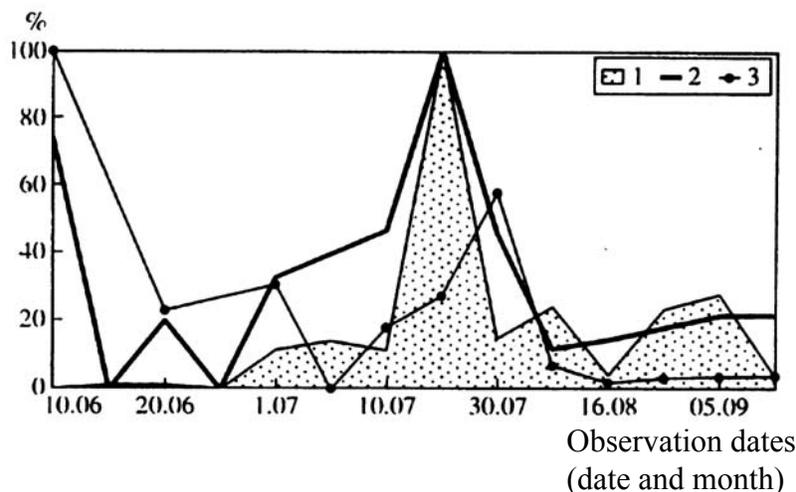


Figure 4.1 Dynamics of concentrations of juvenile roach (1) in the pelagic zone of Ivan'kovskoe reservoir and its food sources in the pelagic (2) and littoral (3) zones (% of the maximum value)

Therefore, fish may be entrained in the water intake zone because prolarvae leave the spawning locations in the area of the water intake, or because active migration occurs. However, the majority of fish gets entrained in the water intake zone due to passive migration induced by the water intake current. To make the passive migration happen, the fish needs to be present in the pelagic zone. The presence of fish in the pelagic zone can be made possible due to the mechanisms of the first and the second levels. These mechanisms primarily depend on hydraulic conditions and orientation capabilities in rivers and reservoirs. For the reservoirs, the major mechanism of the first level is considered to be associated with non-specific behavioral reactions, and the major mechanism of the second level is “neutralization” of rheotaxis due to poor orientation conditions.

### 4.3 Migratory Fish Behavior in Water Intake Zone

It is necessary but not sufficient for the fish to be entrained in the water intake zone for downstream migration to occur. To assure downstream migration, the fish needs to be transferred towards the gatewell and go through the gatewell to the tailwaters. The fish distribution studies show that it is in the tailwaters that the juvenile fishes accumulate (Pavlov et al., 1991a, 6). Their concentration in the tailwaters is always higher than away from the dam (Table 4-2). Consequently, the migration behavior changes when the fish goes to the water intake zone, i.e., the young fish becomes more active, which results from the specific conditions there. Let us describe those conditions, as well as how they affect fish migration and its mechanisms.

Let us remind you that the water intake influence zone, or water intake zone is an area of the reservoir adjacent to the dam where the current velocity differs from the average current velocity in the reservoir and its value goes up from the upper border towards the gatewell. In that area, the flow moves faster and the current velocity vector may deviate from the horizontal direction. The fish is likely to see immobile markers. In other words, there is much more information there for fish than in the pelagic zone outside the water intake zone. It makes orientation easier for the fish and, consequently, many of their reactions may be initiated to help them avoid the gatewell.

Two more zones can be distinguished in the water intake zone where the young fish behavior will be different, i.e., reaction zone and zone of critical velocities (Fig. 4.13).

**Table 4-2 Average concentrations of juvenile fishes (no./1,000 m<sup>3</sup>) in summer in the pelagic zone of the water intake zone and in the pelagic zone 2 – 3 kilometers away from the water intake zone**

Species	Water intake zone	Pelagic zone of reservoir
Sheksninskoe reservoir		
European smelt	4.34	1.23
Roach	1.12	0.05
Bleak	1.31	0.76
Carp bream	0.89	0.10
European perch	48.50	3.45
Pikeperch	5.54	1.34
Ivan'kovskoe reservoir		
Roach	0.10	0.0
Bleak	1.90	0.23
Carp bream	0.60	0.15
European perch	0.60	0.24
Pikeperch	1.40	0.65
Uglichskoe reservoir		
European smelt	0.04	0.08
Roach	0.40	0.30
European perch	0.60	1.20
Pikeperch	0.40	0.00
Ruffe	0.60	0.13

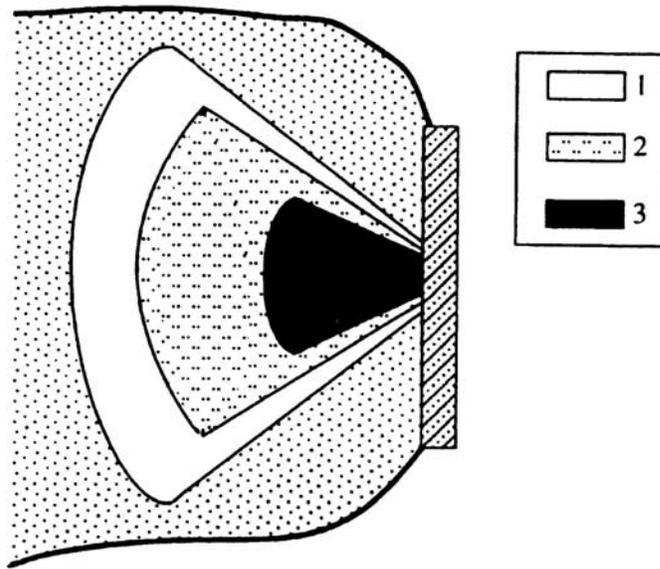


Figure 4.13 Locations of reaction zone (2) and zone of critical velocities (3) in the water intake zone (1)

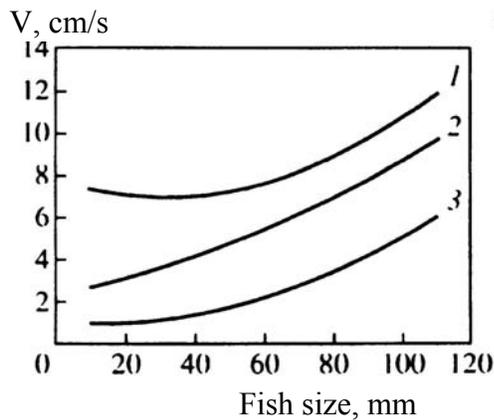


Figure 4.14 Threshold velocities for charr (1), Crucian carp (2), and roach (3) (Pavlov, 1979)

The reaction zone is an area in the water intake where the fish can resist drifting with the current. Changes in the abiotic conditions there reach threshold values for certain behavioral reactions of fishes. They have rheotaxis, as well as the reactions aimed at maintaining the certain depth levels typical for their habitat (hydrostatic reaction and photoreaction).

The zone of critical velocities is located inside the reaction zone. The flow velocity there is higher than the critical velocity for the fish, and, therefore, they drift with the flow to the HPP gateway.

It should also be noted that the behavior of the juvenile fish in the zone of critical velocities does not affect the result of migration because all the juvenile fish species entrained in this zone are bound to go to the gateway. Therefore, the area-specific behavior of the young fish can only be observed in the reaction zone. It needs to be taken into account that the reactions of fishes will

vary there. And first, we would like to describe individual reactions and then we'll try to evaluate their combined effects.

### **Rheotaxis**

The upper (outer) border of the reaction zone is determined by the *threshold current velocity* (the minimal current velocity for initiating rheotaxis). The threshold velocity mostly depends on the light conditions that provides visual orientation of fishes and on the quality (degree of contrast and size) and a number of markers. The threshold velocity varies for various fish species and it increases for the juvenile fishes (Fig. 4.14). The flow turbulence significantly affects the sensitivity threshold of fishes (Skorobogatov et al., 1983). The more intense the turbulence is, the lower the threshold velocity is.

On the whole, the threshold velocity ranges from tenths of a cm/s to several cm/s, depending on biotic and abiotic factors. It should be noted that the current velocities near the borders of the water intake influence zone are in the same range. It means that the upper border of the reaction zone may coincide with the upper border of the water intake influence zone.

The lower (inner) border of the reaction zone is determined by the *critical current velocity* (the minimal velocity when fish cannot resist drifting with the current). The critical current velocity varies for various fish species and various ages and it increases as the fish grows older (Fig. 4.15). The habitat and light conditions also affect this value. Under good conditions for visual orientation, the critical velocity goes up. The water temperature also affects rheotaxis (Fig. 4.16).

Threshold and critical current velocities depend on a species, they change with age and depend on various environmental factors. Specifically, the orientation capabilities in various ecological zones will be different and, consequently, their rheotaxis will be different. Therefore, the reaction zone never has well-defined borders. The borders will vary, depending on biotic and abiotic factors.

The maximum amount of immobile markers in the littoral zone create good conditions for visual (with sufficient light) orientation, as well as for tactile and hydrodynamic orientation of fishes. All these factors reduce the threshold velocity and increase the critical velocity. Therefore, the reaction zone may be larger in size in the littoral zone.

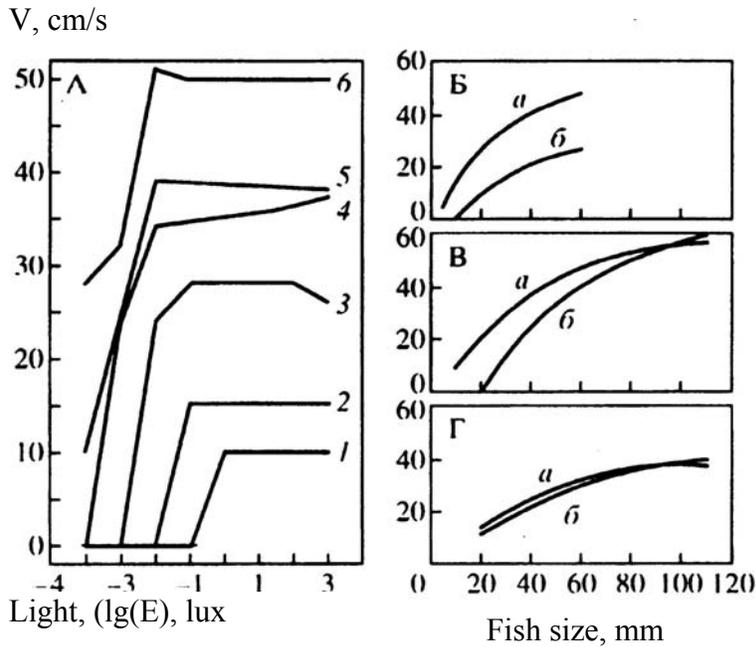


Figure 4.15 Critical current velocity as a function of light conditions for Caspian roach (A), moderlieschen (*Leucaspis delineatus*) (B), roach (B) and Russian sturgeon (Gamma) (ref.: Pavlov, 1979)

Fish size: 1: 8–9 mm, 2: 14–15 mm, 3: 23–25 mm, 4: 27–28 mm, 5: 29–30 mm, 6: 33–34 mm; light conditions: a – in the light, b – in the dark

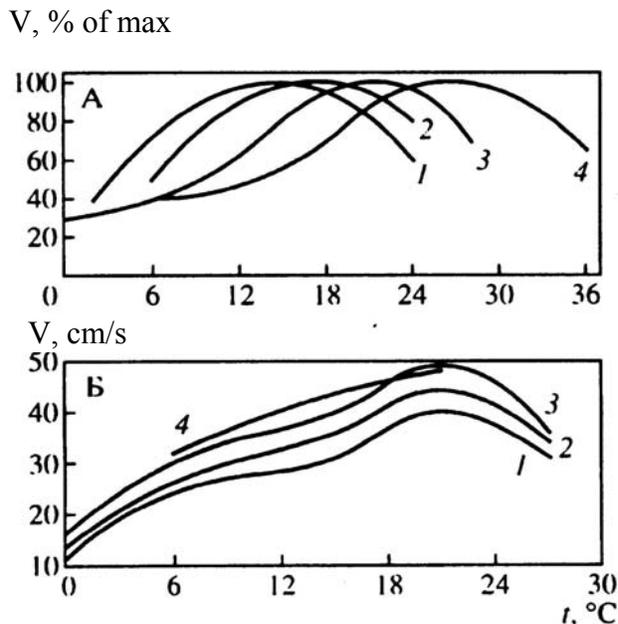


Figure 4.16 Swimming capability and rheotaxis of fishes as a function of water temperature (ref.: Pavlov, 1979)

A – swimming speed: 1 – Sockeye salmon (Brett et al., 1958); 2 – American shad (Fry, 1947); 3 – moderlieschen (*Leucaspis delineatus*); (Pavlov et al., 1972); 4 – goldfish (Fry, Hart, 1948); B – critical current velocity for: moderlieschen (*Leucaspis delineatus*) 40 mm (1); 45 mm (2); 50 mm (3) and European perch 45 mm (4)

In the sublittoral zone, these markers are remote and, therefore, the fish visual orientation is limited. There is less light in the bathyal zone than in the epipelagic zone, and, therefore, the fish cannot see well, but since the bottom is close, the tactile and hydrodynamic orientation is pretty good. In those zones, the difference between the threshold and critical current velocities is lower than in the littoral zone.

There are no visual markers for orientation in the water mass of the pelagic zone. This zone is the worst zone regarding fish rheotaxis, and the reaction zone there is the smallest. The only mechanism for initiating rheotaxis is the acceleration of the flow. The acceleration always occurs because the current velocity increases on narrowing the water intake front.

It has not been thoroughly studied yet how fish react to accelerations. It has been proved though that fish react to centrifugal accelerations (Dijkgraaf, 1933; Gray, 1937; Holand and Holand, 1962; Harden Jones, 1957, 1968). There are very few data on how fish react to linear accelerations. Harden Jones (1956) was the first to detect a reaction of a blind goldfish to linear accelerations of 160 – 200 cm/sec<sup>2</sup>. Other studies (Pavlov, Turukov, 1995) have shown that the juvenile dace (*Leuciscus leuciscus*) reacts to linear acceleration of over 15 cm/sec<sup>2</sup>. There are no data on how the accelerations affect juvenile migratory fish. There have only been some indirect data that the negative gradients of flow velocity near the barriers make the young fish avoid them (Pavlov, Turukov, 1988). Our unpublished observations show that the rheotaxis of young migratory fish “restores” if the flow velocity drops.

### **Compensating Pressure-Induced Movement**

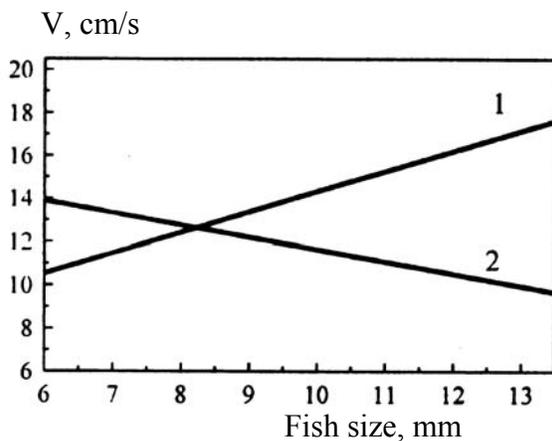
An important factor that will affect fish behavior in the water intake zone is deviation of the velocity vector from the horizontal direction, i.e., the presence of the vertical component in the current velocity. The vertical component makes the fish transfer from one depth to another. With this transfer, the hydrostatic pressure changes. It is known that, depending on the pressure value and the length of adaptation to the pressure, many behavioral characteristics of fishes change (Alexander, 1959; McCutcheon, 1966a; Tsvetkov, 1969, 1974; Pavlov, 1979; Skorobogatov et al., 1987; and other authors). Therefore, the vertical currents may induce certain hydrostatic reactions in the migratory fish. These reactions may prevent them from getting into the HPP turbines. Let us dwell upon how it may happen.

Changes of hydrostatic pressure may cause various behavioral reactions of fish. When the changes are not significant, spontaneous motions may occur (throbbing of fins, yawning, shuddering, “freezing”, chaotic rushes, descending to the bottom and hiding). The sensitivity threshold to the pressure change in still water is within the 10 cm range of the water column. For example, minnows (*Phoxinus phoxinus*) show a hydrostatic reaction when changing the depth by 0.5 – 1 cm (Dijkgraaf, 1941), ten-spined stickleback (*Pungitius pungitius*) have these reactions when changing the depth by 3 – 6 cm (Tsvetkov, 1975), and goldfish and *Mugil cephalus* by 0.5 – 2.0 cm (McCutcheon, 1966b). When the pressure changes significantly, the fish will always have a hydrostatic reaction that makes them move vertically to the depth levels where their buoyancy becomes neutral. These reactions will be aimed at achieving neutral buoyancy because this is energetically the most optimal condition for them (Tsvetkov, Danilov, 1979). It is

important to know that such movements can occur even *without any possibility of visual orientation* (Strotkoetter, 1960). Without visual orientation, the hydrostatic reactions will be controlled by the directions of the hydrostatic pressure changes.

Compensating movement of fish that is associated with the vertical movements is important for understanding the interactions between the fish and the water intake current in the water intake zone. Those vertical movements will occur with or without rheotaxis. There have been very few studies on the compensating hydrostatic reactions, but they have been intensely studied lately. Therefore, let us provide more detail on the fish behavior when they change the depth of their habitat.

To quantitatively estimate the compensating pressure-induced movements, a parameter such as the threshold pressure change is used (the minimal pressure change that initiates the compensating movement of the species). A study on the bleak larvae (Kostin 1990 б) shows that the pressure increase by 5 – 10 cm of the water column makes 50% of the individuals ascend, while the pressure increase by 90 cm of the water column makes 100% of the individuals ascend. These values determine the upper border of the reaction zone in the pelagic water mass where there is no rheotaxis observed.



**Figure 4.17** Critical velocities of horizontal (1) and vertical descending (2) flows for bleak larvae (ref.: Kostin, 1990б).

The lower border of the reaction zone determined for the compensating pressure-induced movements for the early juvenile fish practically coincides with the rheotaxis zone. It has been proven by the data on the current critical velocity for fish in horizontal ascending and descending flows (Fig. 4.17).

### Combination of Reactions

Both rheoreaction and the compensating pressure-induced movements have been observed to occur together in the water intake zone of the studied reservoirs, specifically, near the sloping areas of the sublittoral and bathyal zones. As a rule, in those areas, the fish react to the value and

direction of the velocity current vector. It has been proved by the fact that the fish body axis and the flow direction coincide (Skorobogatov, Pavlov, 1991).

If the pressure-induced reaction appears together with the rheotaxis, the sensitivity threshold towards the pressure may change. Our studies on the bleak and moderlieschen (*Leucaspis delineatus*) juvenile fish show that the threshold pressure change in the flow is 20 – 25% higher than in stagnant water (Skorobogatov et al., 1995). It does not depend on the current velocity and the intensity of the pressure change, and it only depends on the size of fishes (Fig. 4.18), the adaptation pressure value, water temperature (Fig. 4.19) and light (Skorobogatov et al., 1997).

Further pressure change will make the fish lose the rheotaxis and they will drift with the current. Such pressure change is defined as critical. Its value does not depend on the intensity of the pressure change, but it goes up with an increase of the fish size and it goes down with the increase of the current velocity (Fig. 4.20). It also goes down if the water temperature goes down (Fig. 4.21).

Consequently, if the rheotaxis and the pressure-induced reaction occur simultaneously, the fish is transferred to the depths with the pressure different from the one to which the fish has originally adapted. If the change of the hydrostatic pressure exceeds the threshold value, the young fish will try to compensate for the pressure change, initiating rheotaxis and the pressure-induced reaction. If the pressure change exceeds the critical pressure, the fish will drift towards the water intake.

In the pelagic zone of the water intake influence zone, the fish migration from one depth level to another will cause changes in hydrostatic pressure, as well as in water temperature and light. Specifically, if the fish descend, the pressure goes up and the water temperature (in summer) and light go down. Decrease of water temperature and light may also change the fish behavior. The available literature has data on the fish behavior with changes of the following environmental factors:

Flow gradients (Pavlov, 1979);

Light (Moor, 1955; Brett, 1983; Protasov, 1957; Pavlov, 1959; Girsas, 1969, 1971, 1972, 1973;

Legky, Pavlov, 1987; Legky, 1989; Aminov, Radenko, 1990 and other authors);

Water temperature (Bugrov, 1982, 1985; Konstantinov et al., 1991; Lapkin et al., 1977, 1979;

Poddubny et al., 1978; Svirsky, Zgolovanov, 1991, 1992; Karlsson et al., 1984;

Williams, Brauer, 1987; Hirai, Umenoto, 1991, and other authors).

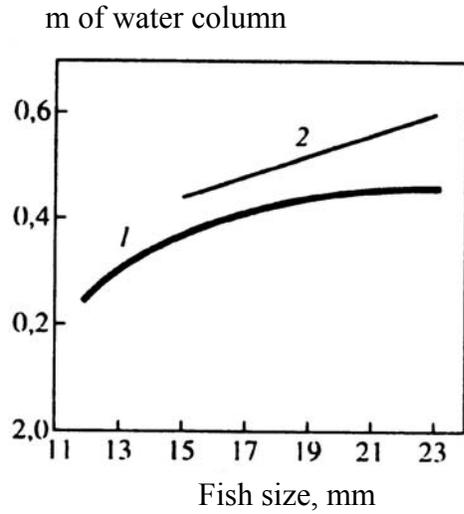


Figure 4.18 Threshold pressure change ( $p$ ) for the young moderlieschen (*Leucaspius delineatus*) (Skorobogatov et al., 1995)

1 – in the light; 2 – in the dark

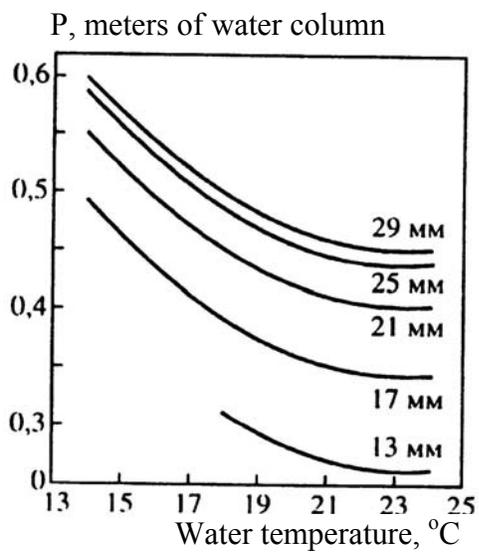


Figure 4.19 Change of threshold pressure ( $P$ ) as a function of temperature for the moderlieschen (*Leucaspius delineatus*) with different body length (Skorobogatov et al., 1997)

P, meters of water column

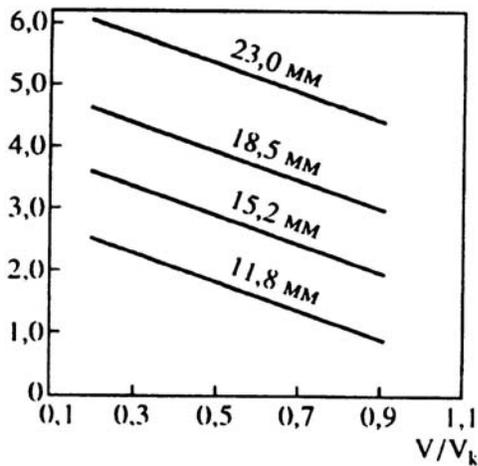


Figure 4.20 Critical pressure (P) change as a function of  $V/V_k$  for the moderlieschen (*Leucaspius delineatus*) with different body lengths (Skorobogatov et al., 1995)

$V/V_k$  is the ratio between the flow velocity and the current critical velocity for the fish

P, meters of water column

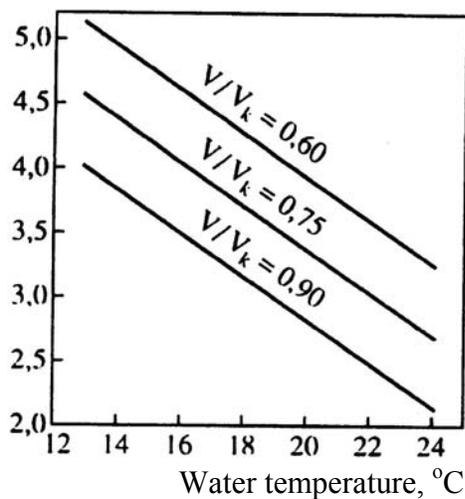


Figure 4.21 Change of threshold pressure (p) as a function of water temperature for the moderlieschen (*Leucaspius delineatus*) with the body length of 20 mm (Skorobogatov et al., 1997)

$V/V_k$  see Fig. 4.20

Many publications indicate the best environmental parameters for fish (Konstantinov, Zdanovich, 1985, 1986, 1987; Konstantinov, Martynova, 1992; Perevoznikov, Golubkova, 1987; Compeau, Guderley, 1984; Spoor, 1990, and other authors). But these data cannot be directly applied to the description of the juvenile fish behavior in the water intake zone. In the water intake zone, the fish are *simultaneously* exposed to a number of various factors, i.e., rheofactors, pressure change-induced factors, temperature change-induced factors and light change-induced factors due to a change of the depth level resulting from descending or ascending flows. It is very

difficult to study the behavior and distribution of fish exposed to all those factors simultaneously, but such studies have already been started.

Our studies on the carp and European perch juvenile fish (Pavlov et al., 19976) show that all these factors are sure to affect the fish distribution. However, the resulting behavior and distribution cannot be considered to be the direct sum of their reaction to each individual factor. Under various conditions, the degree and probability of the fish reactions to those factors may vary, and, in some, cases, even the direction of these reactions may change.

The water temperature affects the fish distribution more than light change, but the specific water temperature comfortable for the majority of fishes depends on the light conditions, hydrostatic pressure and the pressure value to which the fish is adapted. Apart from the average temperature value, the temperature gradient is also important for the fish distribution. The gradient over 7°C/m prevents the fish distribution. For open swim bladder fish (carp family), it is even more important than for the closed swim bladder fish (European perch).

Pressure is one of the strongest factors affecting fish distribution and behavior. The presence of the hydrostatic pressure gradient may change the photoreaction of the closed swim bladder fish (European perch), and their preliminary adaptation to a high pressure increases the average depth of the fish distribution under all temperature and light conditions.

Therefore, in the water intake zone, the young fishes can react to the water intake currents even without any visual or tactile markers due to the presence of rheo-reactions, pressure change-induced reactions, temperature change-induced reactions and light change induced reactions. The sensitivity of fishes towards environmental changes is high enough to try to resist the water intake current. Due to their resistance, the young fish inhabiting the water surface layers do not perform downstream migration, but accumulate in the water intake zone. However, it is difficult to provide quantitative estimations of fish behavior in the water intake zone. It could be done if the fish hierarchy and preference towards various environmental factors are studied.

#### 4.4 Major Factors of Fish Migration from Reservoirs with Slow Water Exchange and Their Mechanisms

Fish downstream migration can be described by many biotic and abiotic environmental factors. These factors include but are not limited to the following: HPP water intake volume, light conditions, nutrition conditions, and ecological zones of water intake. Below we would like to discuss how each of these factors affects the fish downstream migration from reservoirs with a slow water exchange.

##### **HPP Water Intake Volume**

The HPP water intake volume determines the total seasonal or annual volume of water that goes through the HPP, and it is characterized by a change of the flow rate that affects such parameters of the fish downstream migration as a number of migrants, their concentration, species-specific structure, age and size of the migrants.

This factor affects the number of the migrants in two ways. On the one hand, if the concentration of the migrants is stable, its number will depend on the water intake volume. The larger the water intake volume is, the more migrants go through the HPP. On the other hand, if the HPP flow rate changes, the concentration of the migrants may change and, consequently, the total number of the migrants may change. It can be explained by two reasons, i.e., change of how the water intake current affects the ecological zones of water intake and change of the hydraulic conditions near the water intake.

If the HPP water flow rate increases, the water intake zone expands. It can acquire new areas of the reservoir, e.g., the sublittoral and littoral zones where the fish concentration is higher and more fish species of various age and sizes are present. Ultimately, it will result in the increase of the fish concentration in the water intake zone and, consequently, a greater number of the potential migrants. Beyond that, the current velocity increases, resulting in a higher probability of the fish downstream migration. If the HPP water flow rate goes down, just the reverse situation occurs, i.e., the concentration and the number of the migrants go down and fewer species, sizes and ages are present there.

**Table 4-3 Average concentration of migrants (no./1000m<sup>3</sup>) in July – August from Ivan’kovskoe Reservoir**

Species	1979	1980
Ruffe	0.328	8.045
Carp bream	0.13	2.84
Roach	0.275	0.645
European perch	0.755	1.29
European smelt	0.550	0.725
Pikeperch	2.405	1.84
Bleak	5.585	0.582

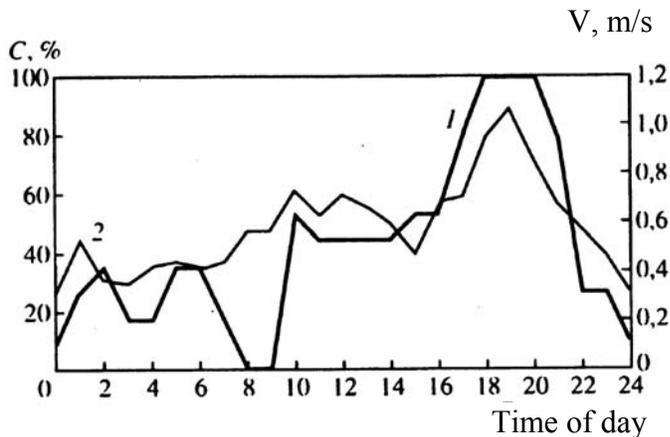
The studies of the Ivan’kovskoe reservoir (Pavlov et al., 1984) for the same season, but in different years, show that the concentration of the migrants increased by more than a factor of 2.5 with the increase of the HPP water flow rate by a factor of 3 (Table 4-3.). The concentration of the migrants increased due to the intensification of the downstream migration of bleak, roach, and ruffe, i.e., those species that primarily inhabit the littoral and sublittoral zones, as well as the bathyal zone. However, the HPP flow rate increase did not affect the concentration of European smelt, pikeperch and perch that inhabited the pelagic zone at that time. This example has illustrated that, in many cases, the increase of the HPP water flow rate changes the concentrations of those fish species that primarily inhabit the littoral and sublittoral zones.

It should also be noted that the change of the HPP water flow rate will affect the absolute values for both vertical and horizontal gradients of the current velocity near the water intake. It may cause either increases or decreases of the migratory fish concentration. In the pelagic zone, the young fish practically do not have any accessible markers on which to base rheotaxis, and, therefore, they drift towards the gatewell. On approaching the gatewell, the values of the vertical and horizontal gradients of the current velocity go up and, with the HPP flow rate increase, they

may even exceed the critical velocity values. If that happens, the fish that used to resist the current prior to the HPP flow rate increase will no longer be able to do that and, therefore, they will drift to the HPP gateway. The conclusion is that the HPP water flow rate increase can increase the migratory fish concentration until the zone of critical velocities embraces the entire fish habitat.

This mechanism can be illustrated by the studies at the Sheksninskoe reservoir (Pavlov et al., 1991a) where the migratory fish concentration as a function of the HPP flow rate was evaluated by means of the association coefficient. It was shown that there is a certain positive association between the flow rate and the concentration of the European perch ( $R_a = 0.71$ ) and European smelt concentration ( $R_a = 0.69$ ) at the time when they inhabit the pelagic zone of the reservoir. However, no such correlation has been observed for the Cyprinidae larvae. In our opinion, it has been different for the Cyprinidae larvae because they stay at the depth of 0.5 – 2.2 m, i.e., in the epipelagic zone, while the European perch and European smelt larvae inhabit 5.8 and 7.9 m, respectively, i.e., the bathy-pelagic zone. In other words, the Cyprinidae larvae are located above the critical velocity zone and, consequently, their concentration does not depend on the HPP flow rate. The European perch and European smelt larvae are located within the upper border of the critical velocity zone and, therefore, their concentrations are affected by the HPP flow rate.

The association coefficient was pretty high (0.68) for the young pikeperch that migrated from Al. Stambolijski reservoir. But that reservoir had a great number of active migrants (Pavlov et al., 1988) and, therefore, we cannot exclude the fact that the HPP flow rate increase has expanded the reaction zone for the young pikeperch and improved their orientation capabilities, thereby intensifying their downstream migration.



**Figure 4.22** Current velocity in the HPP incoming flow and daily dynamics of downstream migration of whitefish (*Coregonus sp.*) older than one year from Ust'-Khantajskoe reservoir

C – ratio of the concentration of the migrants in the sample and its maximum value (1); V – current velocity (2)

One of the examples of how the HPP flow rate increase affects downstream migration is the migration of sardine cisco (*Coregonus sardinella*) and peled (*Coregonus peled*) through the Ust'-Khantajskaya HPP. That HPP sharply increases the flow rate twice a day to accommodate the peak electrical loads, which results in the increase of the current velocity in the incoming flow. The analysis of the daily dynamics of the fish migration has shown that the concentration of the

migrants depends on the current velocity. With the current velocity of over 0.7 m/s, the concentration of the migrants increased significantly (Fig. 4.22). The coefficient of the ranking correlation for the indicated values is 0.77, which testifies a strong connection between the concentration of the migrants and the current velocity in the channel.

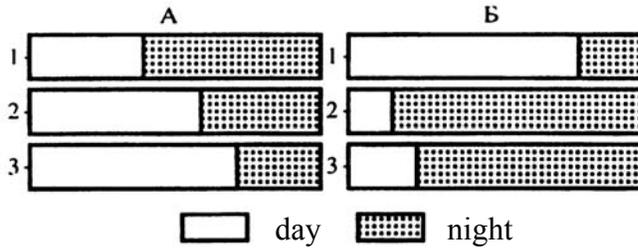
If the HPP water flow rate goes down, the zone of the critical velocities shrinks. In some cases, the zone of the critical velocities does not reach the fish habitat zone, thereby eliminating the downstream migration. It has been observed in Al. Stambolijski reservoir where, with the flow rate below 5 m<sup>3</sup>/s, the pikeperch migration stopped, and, with the flow rate 1.0 m<sup>3</sup>/sec, the ruffe migration stopped.

Therefore, the change of the water volume (flow rate) affects downstream migration and may also affect the migratory fish concentration, as well as the species-specific structure, age and size of the migratory fish. However, the degree of influence of the flow rate change can be disguised by seasonal and daily tendencies in the migratory fish concentrations.

## **Light**

Light affects the daily dynamics of young fish downstream migration. It means that, in the rivers, the fish get entrained in the current in the evening because there is less light (Pavlov et al., 1997), and, also, the fish stop displaying rheotaxis due to the reduction of light below the threshold values for visual orientation in the flow (Pavlov, 1970; Pavlov, 1979; Pavlov et al., 1981).

In the reservoirs, light affects the daily dynamics of fish migration in a more complicated way. Apart from rheotaxis, daily vertical movements in the pelagic zone are also important. The concentration of migrants will increase if the fish habitat depth level and the water intake depth level coincide. Specifically, in Sheksninskoe reservoir, the larvae of most fish species stayed closer to the surface in the daytime than at night. The European smelt larvae behaved in the opposite way (Pavlov et al., 1991a). For comparison, Fig. 4.23 provides the concentrations of the European smelt and pikeperch larvae in the epipelagic and bathy-pelagic zones in front of the gateway and their concentration in the HPP tailwaters. The gateway of this HPP is located in the bathy-pelagic zone. The migration intensity of those fish species is higher when the larvae are located as deep or almost as deep as the gateway, i.e., in daytime for the European smelt larvae and at night for the pikeperch. Consequently, vertical daily movements of young fish associated with light changes may affect the intensity of migration from the reservoirs during the day. It happens when, while descending, the fish enters the zone of critical velocities and, while ascending, it goes above this zone.



**Figure 4.23 Concentrations of European smelt larvae (A) and pikeperch larvae (B) in the epi-pelagic (1) and bathy-pelagic (2) zones in front of the water intake and in the tailwaters of Sheksninskaya HPP (3) in the middle of the day and in the middle of the night**

Therefore, the light changes primarily affect vertical daily movements of fishes. If the water intake gateway is located in the littoral and sublittoral zones of the reservoirs, the influence of the light changes may be, as in rivers, connected to the change of conditions for rheotaxis.

### **Nutrition Conditions**

Nutrition conditions in the reservoir and the peculiarities of fish feeding affect spatial distribution of fishes and, in many cases, their migrations. It has already been mentioned in this book that downstream migration may occur if there is a lack of food in the locations of breeding. This historic reason for downstream migration is not considered to be the direct reason of the passive migration of young fishes from the reservoirs with a slow water exchange. As a matter of fact, the Cyprinidae larvae in the Ivan'kovskaya HPP water intake zone are as well-fed as those downstream. The feeding grades for the water intake zone inhabitants and for the migrants are 1.1 and 1.3, respectively. The percentage of hungry fish is also similar, i.e., 15 and 17%, respectively.

However, our special studies conducted together with V.N. Mikheev in Al. Stambolijski reservoir (Pavlov et al., 1988), have shown that the nutrition conditions can still affect the young fish downstream migration. But this influence is represented not by food availability, but by the peculiarities of the search-related feeding behavior of fishes. In other words, due to the daily changes of the search-related feeding behavior, the young fish may change its location, thereby either entering the water intake zone or leaving it. The analysis of the daily dynamics of the downstream migration of pikeperch and ruffe, three behavioral food search-related mechanisms have been identified. These mechanisms intensify downstream migration if the gateway is located in the bathy-pelagic zone. These mechanisms are as follows:

- fish descend to deeper layers after active feeding, thereby entering the water intake zone;
- fish ascend from the bottom where they feed on zooplankton and, losing orientation, they drift to the water intake zone with the current;
- food search activity increases during the vertical movements, resulting in a loss of orientation for the fishes in the bathy-pelagic zone, thereby forcing them to move to the critical velocity zone.

Beyond that, the nutrition conditions can be one of the reasons for accumulation of fish in the water intake zone by the HPP gateway. As it has been shown earlier (Table 4-2), the concentration of young fish in the water intake zone is usually higher than in the adjacent pelagic

zone. One of the reasons for that may be a higher concentration of zooplankton in the water intake zone. In any case, the Cyprinidae and Percidae larvae have appeared to be better-fed in the Ivan'kovskaya HPP water intake zone than outside it (Cyprinidae – 1.1 and 0.77; Percidae – 2.0 and 1.6, respectively). It is obvious that such accumulation of fish in front of the dam may increase a number of the fish migrants due to the increase of the number of fish exposed to the water intake currents.

The situation is different for the active-passive and active downstream migration when a lack of food in the fish habitat makes the fish migrate. Such migrations are well-known for the amphidromous fishes, specifically, for young pikeperch and carp bream when they migrate from the reservoirs (Syrovatsky, 1953; Potekhina, 1956; Gorodnichij, 1962 and other authors). E.B. Potekhina (1956) indicates that downstream migration is very intense when the pikeperch (35 – 50 mm long) and carp bream (40 – 46 mm long) acquire carnivorous habits and the zooplankton biomass declines. The percentage of “hungry” pikeperch at that time increased up to 50 – 72%.

According to V.K. Nezdolij's data for Kapchagajskoe reservoir (Pavlov et al., 1981), the spontaneous downstream migration of young pikeperch occurred when there was a drastic decline of plankton availability in the headwaters. Many species that migrated into the tailwaters appeared to have empty stomachs. It is also known that, under unfavorable nutrition conditions and due to inability to leave the reservoir, numerous pikeperch losses have been observed (Syrovatsky, 1953; Fesenko, 1953; Potekhina, 1956). At the same time, A.E. Gorodnichij (1978) indicated that pikeperch downstream migration immediately stopped as soon as the food availability in the reservoir improved.

The Al. Stambolijski reservoir data make it possible to track the downstream migration of pikeperch and ruffe as a function of changes of their feeding conditions. Early larvae of pikeperch and ruffe appear in the pelagic zone of the reservoir and start external feeding practically at the same time. Since their sizes are comparable, they feed on small planktonic crustaceans. The larvae of both species seem to be well-fed. Growth of their feeding needs makes them eat more, and the decrease of the zooplankton concentration may worsen their feeding conditions. It is especially true for the large *Daphnias* (the major food for late larvae and fry of pikeperch) that practically disappear in early June.

The analysis of various factors has shown that it is in early summer that the nutrition conditions for the young fish becomes especially bad. In our opinion, it is this reason that makes practically all young pikeperch species move closer to the shore, while the ruffe young species first descend to the bottom and then ascend near the shore too. At that period, ruffe start feeding on chironomid larvae, and the largest pikeperch fry start feeding on young of other fish species. However, even with the new food sources, their feeding conditions at that time are much worse than those for the early larvae. It may be explained by the fact that there is a very small benthos biomass and very few potential young fish prey available.

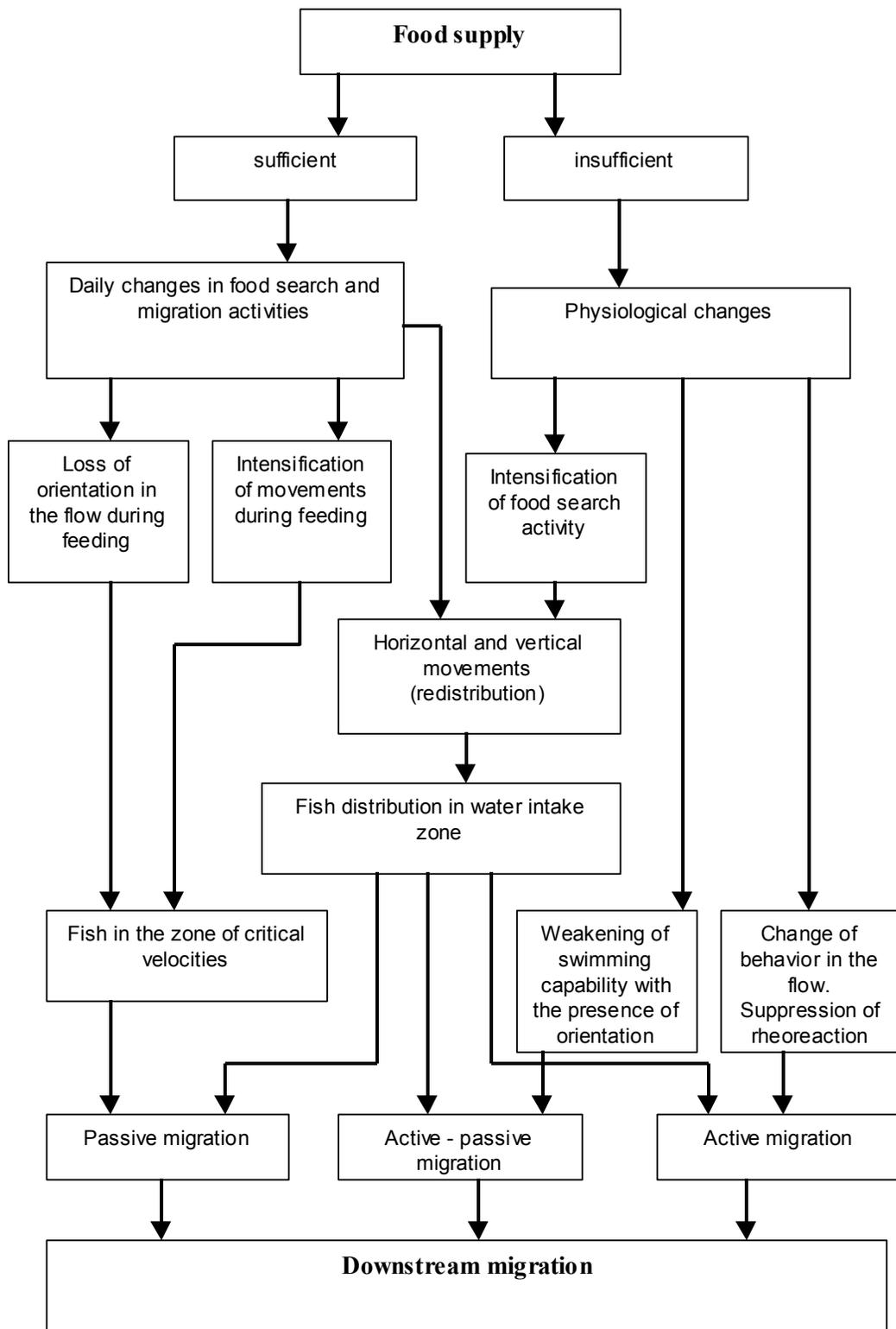
Due to worsening of the feeding conditions, mobile schools of pikeperch have been observed in the littoral area that descended to the bottom after a certain period of time. Then they performed downstream migration from the reservoir even with the lower HPP flow rate. The most intense migration was observed in July when the maximum concentration of the migrants reached 6.0

individuals/m<sup>3</sup>, with the average migrant concentration being 0.4 individuals/m<sup>3</sup>. Such a high concentration indicates that the pikeperch fry tend to select the water intake zone. One of the arguments to defend this statement is that, with the flow rate of 10 m<sup>3</sup>/s, the radius of the zone of critical current velocities for the fry was only 2 meters and the area of the zone was 6.3 m<sup>2</sup> (the total area of the reservoir is 10,860,000 m<sup>2</sup>). It reminds us of E.V. Potekhina's statement (1956) that, during the intense downstream migration, the young pikeperch goes to the zones with any strong current. It is the water current that attracted the young pikeperch to the water intake zone of Al. Stambolijski reservoir. At that period, mass migrations of hungry fry from the reservoir to the mouths of the streams were observed.

Unlike pikeperch, downstream migration of ruffe has been observed for a longer period of time, i.e., from spring through the fall, but its intensity was much lower. The numbers of migrants, as a rule, grow with the HPP flow rate increases. Though the feeding conditions worsened in early summer, it did not cause "spontaneous" migrations, as it did with the pikeperch. The reasons for such drastic differences in how a lack of nutrition affects both species may be related to various intensity of their metabolism, growth, and, consequently, feeding needs. Beyond that, the ruffe is much smaller than the pikeperch and the ruffe fry feed on benthos. It is known (Ivlev, 1955) that the species feeding on benthos are more tolerant to a lack of food than those that feed on plankton. Therefore, the pikeperch fry that feed on zooplankton during the first year of life and that grow very fast are less tolerant to food deprivation than ruffe fry. Hence their more intense migration activity during the period preceding the period of their mass migration.

Therefore, one of the reasons for mass active-passive or active downstream migration of fish from reservoirs with a slow water exchange may be insufficient food availability, causing their redistribution and change of behavior, i.e., formation of mobile schools and active migration to the areas of the reservoirs with well-defined strong currents.

Studies on a number of HPP dams have made it possible for us to obtain a better understanding of the role of nutrition in fish downstream migrations from the reservoirs with a slow water exchange (Pavlov, 1979; Pavlov et al., 1981; Pavlov et al., 1988). Fig. 4.24 gives a schematic presentation of how nutrition mechanisms affect fish downstream migration (Pavlov et al., 1988). It should be noted that this schematic reflects both low and sufficient food supply for the fishes. The nutrition factor works through both the mechanisms of the first and third orders and also through the mechanisms of the second level.



**Figure 4.24 Schematic presentation of how the nutrition mechanisms affect the fish downstream migration (Pavlov et al., 1988)**

Regarding the mechanisms of the first and third levels, associated with the fish distribution, not only the pelagic distribution of fish is important, but also the correlation of this distribution with the water intake zone. Both for the insufficient and sufficient food supply, vertical and horizontal movements of young fish occur, resulting in their migration to the water intake zone. However, with the insufficient food supply, this redistribution is caused by the change of the physiological state of fish, intensification of the food search activities and migration outside the permanent habitat area. With sufficient food supply, fish movements are associated with the regular daily changes of food search activities and migrations within the permanent habitat area.

The mechanisms of the second level work with a low availability of food due to the change of the fish behavior in the flow (drifting with a capability for orientation and a drop of swimming capability or suppression of rheotaxis, as well as active movement with the current). If the food is readily available, the rheotaxis is pretty high, and the fish appear to be in the zone of critical velocities only due to a lack of orientation in the flow during feeding (Ukhtomsky's principle) or due to the rushes during hunting. These behavioral features result in the passive downstream migration if there is enough food and in active or active-passive migration if there is a lack of food.

Therefore, the nutrition conditions affect downstream migration in various ways as it is presented in Fig. 4.24. The presented schematic is, however, very general and, in some cases, hypothetical, and, therefore, some further studies are required in this field.

### **Ecological Zones of Water Intake**

The ecological zones of water intake (EZWI) affect many parameters of the downstream migration from reservoirs with a slow water exchange. Specifically, they affect such parameters as species specific structure, age and size of the migrants, as well as seasonal and daily dynamics of migration and migration index. All of these interactions have been illustrated in Chapter 3. Let us describe now why and how the EZWI affect some parameters of the downstream migration.

*Species specific structure, age and size of migrants.* Many fish species prefer certain ecological zones, depending on their ontogenetic period. Therefore, only those species can be found in the water intake zone that inhabit the ecological zones affected by the water intake current. If the water intake zone includes several ecological zones, there will be more species found there. Consequently, species specific structure and the age of the migrants will depend on their location in certain ecological zones. Since the fish body length also depends on age, the sizes of the migrants will also depend on the EZWI.

Downstream migration from reservoirs significantly depends on conditions for fish orientation and locomotive capabilities in the water intake zone. For example, the young fish would have the best conditions for orientation and finding shelters to avoid currents in the littoral zone. These conditions will be much worse in the bathy-pelagic zone where there will be no shelters available. Beyond that, the bathy-pelagic zone has lower water temperatures, thereby affecting fish locomotive capabilities. Therefore, the capability to resist the water intake currents (with the

similar motivation) will, to a large extent, depend on which ecological zone the fishes are located.

*Seasonal dynamics of migration.* Taking into account the fact that the development of the young fish depends on the environmental conditions that, in their turn, depend on the climatic conditions in various seasons, the change of location depends on the season. Besides, fish perform regular seasonal migrations inside the reservoir (spawning, feeding and hibernation migrations, etc.), changing the ecological zone of their habitat. It means that, depending on the season, the fish may be found in various ecological zones of the reservoir, and, consequently, in various areas of the water intake zone. Therefore, the seasonal dynamics of downstream migration is closely connected with the EZWI.

*Daily dynamics of migration.* Some fish species perform daily vertical movements. These movements may result in entrainment in the water intake zone or, on the contrary, leaving the water intake zone. Apart from vertical movements, young fish may perform horizontal daily movements in lakes and reservoirs (Pavlov and al., 1985a). All those movements may result in changing the ecological zones in both the reservoirs and in the water intake zone associated with the EZWI. These movements can accelerate or decelerate the downstream migration process, thereby controlling dynamics of migratory fish daily concentration.

*Migration index.* The intensity of migration depends on how well the fish habitat area coincides with the water intake zone, and the length of the migration depends on how long they coincide. These parameters will vary from species to species and they depend on the location of the water intake zone relative to the ecological zones of the reservoir, i.e., on the ecological zones of water intake. Since the length and intensity of the migration control the number of the migrants and, consequently, the percentage of the migratory fish in the total number of fish in the reservoir, the migration index as it is defined in this book depends on the EZWI.

Therefore, the ecological zones of water intake will provide both necessary and sufficient conditions for downstream migration because they will control what species will be found in the water intake zone due to their behavior and distribution and how successfully they can resist the intake current. As a matter of fact, the EZWI imply and summarize various correlated environmental factors that significantly affect the downstream migration from the reservoirs with a slow water exchange.

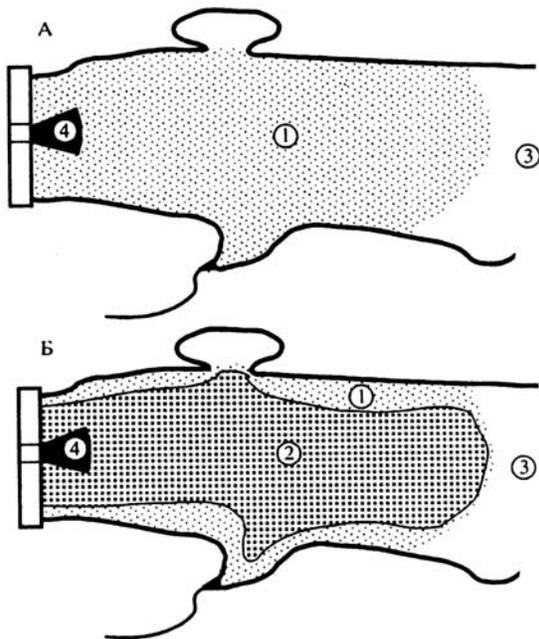
## 4.5 Model for Fish Downstream Migration from Reservoirs

Modeling of natural processes makes it possible to evaluate the authenticity of the obtained data and identify the problems for further research. Modeling is also considered to be a very important component of the systems analysis that allows us to adequately study and control complex processes (Jeffers, 1981). Fish downstream migration is definitely one of those complex processes. We have developed a model for passive downstream migration that helps identify the number of fish migrating from the reservoir. To build this model, we have taken into account the major mechanisms that initiate downstream migration from the reservoirs with a slow water

exchange. It is the quantitative approach to the contributions of these mechanisms that has made it possible to develop this model.

Various fish species inhabit the open pelagic zone of the reservoir during various stages of ontogenesis. Depending on the type of fish distribution in the reservoir and on frequencies of their migrations to the pelagic zone, one or several downstream migrations can be observed for various species.

When the fish species stay in the pelagic zone, a certain water volume goes through the water intake zone. The volume of the part of the reservoir adjacent to the water intake zone with its coves and tributaries is equidimensional to the water volume that goes through the water intake. This part of the reservoir is defined as *the water discharge area* (Fig. 4.25). Since the major driving force for drawing the fish towards the water intake zone is the water intake current, only the fish that will be located in the discharge zone will drift to the water intake zone. The pelagic zone of the reservoir is the major fish source for the water intake zone and, therefore, if the fish inhabit the pelagic zone, it will be one of the major conditions of their migration to the water intake zone. Thus, the pelagic zone is defined as *the area of potential fish migration*. However, due to various reasons, not all the fish species will migrate through the HPP water intake zone. For example, in the water intake zone, the fish may intensify their movements due to the information enrichment of the media and, consequently, resist downstream migration. Thus, modeling should be performed for each fish species individually, taking into account its behavior and distribution.



**Figure 4.25** Locations of water discharge area (A) and the area of potential fish migration (B) in the reservoirs

1 – water discharge area; 2 – area of potential fish migration; 3 – reservoir; 4 – HPP water intake influence zone

In general, the major assumptions of the model are as follows:

- At various stages of ontogenesis, the young fish (R) may enter and leave the pelagic zone of the reservoir. Each of these periods will start with entering the pelagic zone, staying in the pelagic zone for a certain time T and leaving the pelagic zone.
- Several age groups can be identified in the process of fish growth and development. The timeframe of these groups will not depend on the periods of ontogenesis, but it will depend on when the fishes enter and leave the pelagic zone.
- Only those fishes will be found in the area of the potential fish migration that, prior to entering the pelagic zone, inhabited the water discharge area.
- In the pelagic zone, the young fishes perform passive migrations with the water intake current towards the water discharge area.
- Only part of the fish migrants that can be found in the water intake zone will perform downstream migration to the HPP tailrace.

Taking into account these assumptions, we can present the mathematical description of downstream migration by means of the following equation:

$$Dc = f(Dc_i) = f(Ks_i \cdot Dd_i), \quad (4.1)$$

where:  $Dc$  – percentage of fish migrated from the reservoir out of the total number of fish in the reservoir;  $Dc_i$  – percentage of fish of one specific age group migrated from the reservoir out of the total number of fish of this age group;  $Dd_i$  – percentage of fish of one age group to be found in the water intake zone, out of the total number of fish of this age group;  $Ks_i$  – migration index that takes into account the percentage of fish of one age group migrating through the water intake out of the total number of fish in the water intake zone;  $i$  - ordinal number of the period when the fish stays in the pelagic zone.

To solve this problem, the following needs to be found: function  $f(Dc_i)$ , value  $Dd_i$ , i.e., the fish that can be found in the water intake zone and coefficients  $Ks_i$  for each age group of the young fish.

### **Calculations of the Amount of Fish Entering the Water Intake Zone**

To estimate how many fishes enter the water intake zone ( $Dd_i$ ), we need to know the number of fish in the area of potential fish migration and in the entire reservoir. We have estimated these values by assuming that the number of fish in the given area is the product of its area ( $S$ ) and the fish density there ( $\rho$ ):

$$N = S\rho, \quad (4.2)$$

The fish will go to the area of potential fish migration from the littoral zone of the reservoir and its tributaries located in the water discharge area (WDA) where the fish used to stay during the previous age group. Therefore, in general, a number of fish of the given age group to be found in the HPP water intake influence zone, can be calculated by the equation:

$$Dd = \frac{Nd}{No + Nqo}, \quad (4.3)$$

where:  $Nd$  is the amount of fish of the given age group to be found in the HPP water intake influence zone within the time period  $T$ ;  $No$  is the amount of fish of the given age group to inhabit the reservoir in the beginning of the time period  $T$ ;  $Nqo$  is the number of fish of the given age group to enter the reservoir from the tributaries during the time period  $T$ .

According to the definition of the area of potential fish migration, the number of fish to be found in the HPP water intake influence zone within the time period  $T$  is equal to the number of fish in that area. This number can be found from the following equation:

$$Nd = Nv + Nqv, \quad (4.4)$$

where:  $Nv$  is the number of fish of the given age group located in the reservoir in the area of potential fish migration;  $Nqv$  is the number of fish entering the area of potential fish migration from the tributaries that go into the water discharge area.

Combining (4.3) and (4.4), we obtain the following:

$$Dd = \frac{Nv + Nqv}{No + Nqo}. \quad (4.5)$$

Dividing the numerator and denominator in (4.5) by  $No$ , we obtain the following:

$$D_d = \frac{Nv/No + Nqv/No}{1 + Nqo/No} \quad (4.6)$$

Taking into account the fact that the fish of the same age group go to the area of potential fish migration from the habitat zone of the previous age group that is located within the water discharge area, the number of fish that enter this area from the reservoir can be calculated as follows:

$$Nv = Ns' \cdot R \cdot E = Ss' \cdot \rho s' \cdot R \cdot E, \quad (4.7)$$

where:  $Ns'$  is the number of fish of the previous age group within the water discharge area;  $R$  is the proportion of fish entering the pelagic zone, from the number of fish of the previous age group inhabiting the water discharge area ( $Ns$ );  $E$  is the proportion of the surviving fish while passing from one age group to another (it is assumed that the death of fish only occurs when they pass on from one age group to another and that the death rate stays the same in the entire reservoir);  $Ss'$  is the habitat area for the fish of the previous age group within the water discharge area;  $\rho s'$  is the average density of fish of the previous age group in the indicated areas.

Similarly, we'll have the following for  $N_o$ :

$$N_o = N_o' \cdot E = S_o' \cdot \rho_o' \cdot E, \quad (4.8)$$

where:  $N_o'$  is the number of fish of the previous age group in the reservoir;  $S_o'$  is the area of the habitat zones for the fish of the previous age group;  $\rho_o'$  is the average fish density of the previous age group in the habitat zones.

Combining (4.7) and (4.8) for ratio  $N_v/N_o$ , we'll obtain the following:

$$\frac{N_v}{N_o} = \frac{S_s' \cdot \rho_s' \cdot R \cdot E}{S_o' \cdot \rho_o' \cdot E} = \frac{S_s' \cdot \rho_s' \cdot R}{S_o' \cdot \rho_o'}. \quad (4.9)$$

The significant point here is the reduction of the mortality coefficient. It means that the proportion of the migratory fish does not depend on the young fish fatalities in ontogenesis.

The values  $N_{qv}$  and  $N_{qo}$  in (4.6) can be presented by means of the corresponding fish concentrations:

$$N_{qv} = W_{qs} \cdot C_{qs}, \quad (4.10)$$

$$N_{qo} = W_{qo} \cdot C_{qo}, \quad (4.11)$$

where:  $C_{qs}$  and  $C_{qo}$  are the average fish concentrations in the tributaries of the water discharge area and the entire reservoir, respectively;  $W_{qs}$  and  $W_{qo}$  are the total inflow of the tributaries going into the water discharge area and the entire reservoir, respectively, for the time period  $T$ .

The average concentration of fish of the same age group that used to inhabit the reservoir can be designated as  $C_o$ .  $C_o$  is equal to the following:

$$C_o = N_o / W_o, \quad (4.12)$$

where:  $W_o$  is the volume of the reservoir.

Combining (4.10), (4.11) and (4.12), we can calculate the following values:

$$N_{qv} = N_o \frac{C_{qs} W_{qs}}{C_o W_o}, \quad (4.13)$$

$$N_{qo} = N_o \frac{C_{qs} W_{qo}}{C_o W_o}. \quad (4.14)$$

Inserting the obtained values  $N_v/N_o$ ,  $N_{qv}$  and  $N_{qo}$  into (4.6) and making all necessary transformations, we'll obtain the equation for calculating the share of fish to be found in the HPP water intake influence zone:

$$Dd = \frac{(Ss' \rho s' \cdot R) / (So' \cdot \rho o') + Cqs / Co \cdot Wqs / Wo}{1 + Cqo / Co \cdot Wqo / Wo}. \quad (4.15)$$

Since equation (4.15) has been obtained for the conditions when the fish of the same age group can go to the pelagic zone of the reservoir from both the reservoir and its tributaries, we'll need to calculate the cases for the fish entering the pelagic zone from either the reservoir or from the tributaries. For the fish entering the pelagic zone from the reservoir we have:  $Cqo = 0$  and  $Cqs = 0$ . Taking this into account, equation (4.15) will be as follows:

$$Dd = \frac{Sw' \cdot \rho s' \cdot R}{So' \cdot \rho o'}. \quad (4.16)$$

Since all the parameters of equation (4.16) only refer to the fish inhabiting the reservoir prior to time period T, equation (4.15) will only be applicable for those cases when the fish enters the pelagic zone from the reservoir only.

If the fish enters the pelagic zone only from the tributaries, we'll have:  $So' = 0$ ,  $Sw' = 0$  and  $Co = 0$ . If we insert these values into (4.15), we'll be dividing by zero, which will not allow us to use this equation for the calculations in case the fish enter the pelagic zone from the tributaries.

Since it is impossible to describe this uncertainty mathematically, let us evaluate the share of fish to enter the water intake zone if they enter the pelagic zone from the reservoirs. For this case, let us assume for (4.5) that  $No = 0$  and  $Nv = 0$ . Then we'll obtain the following:

$$Dd = \frac{Nd}{Nqo} = \frac{Wqs \cdot Cqs}{Wqo \cdot Cqo}. \quad (4.17)$$

Thus, a number of fish of the same age group that will drift by the water intake current in the reservoir and will enter the HPP water intake influence zone is recommended to be calculated by means of the following equations:

if the fish enter the pelagic zone from both the reservoir and the tributaries, equation (4.15) should be used;

if the fish enter the pelagic zone from the reservoir only, (4.16) or (4.15) should be used;

if the fish enter the pelagic zone from the tributaries only, equation (4.17) should be used.

### Calculation of Migration Coefficient

The values of Ksi, the migration coefficient, have been obtained by summarizing the existing data on the regularities of fish downstream migration through HPP dams. The studies on interactions of the young fish with the water intake currents in the HPP water intake influence zone show that not all the fish that enter the water intake influence zone migrate from the reservoir. It can be explained by the fact that, entering the HPP water intake influence zone, the young fish may be affected by a number of factors and acquire some resistance towards the

horizontal and vertical components of the water intake velocity current. Thus, the  $Ks_i$  value primarily depends on how these factors are implemented.

Taking into the account the potential fish resistance to the water intake current, the migration coefficient for the fish of the same age group can be presented as follows:

$$Ks_i = K_{v_i} \cdot Kg_i, \quad (4.18)$$

where:  $K_{v_i}$  and  $Kg_i$  are the coefficients that take into account the resistance of  $i$ -age group fish towards, respectively, the vertical and horizontal components of the water intake current.

Since there are no sufficient quantitative data on the fish interactions with the water intake currents in the HPP water intake influence zone, it seems impossible to give the precise values of these coefficients. Therefore, we give their estimate based on the observations of the young fish downstream migration from the reservoirs.

The  $K_{v_i}$  value determines the correlation between the water intake depth level and young fish habitat depth level in the water intake zone in the daytime. The greater the difference is between those depth levels, the fewer species will enter the water intake. If all the young fish inhabit the HPP water intake zone, all will leave the reservoir. If the difference in the depth levels is 5 m, the proportion of the migrating fish will be 0.7; with the difference of 10 m, the proportion of the migrants will be 0.5; with the difference of 20 meters; the proportion of the migrants will be 0.2; with 30 it will be 0.1; and with 40 meters there will be no migrants.

As Sections 3.4 and 4.4 indicate, the daily occurrence of the young fish in the water intake zone depends on the light conditions and the ontogenesis period. During the early stages of ontogenesis, the fish resistance to the water intake currents is weak and, consequently, they enter the water intake zone continuously and homogeneously all the time. The young fish at stage  $D_2$  and older tend to migrate to the water intake in the dark. It is caused by a loss of their orientation in the flow and change of the habitat depth level. Therefore, for the early period (earlier than stage  $D_2$ ), the migration coefficient  $Kg = 1$ . For later stages, this coefficient can be calculated as the share of the darkness period ( $T_n$ ) of a 24-hour period with the light below one lux:

$$Kg = T_n / 24. \quad (4.19)$$

Taking into account all the previously given data, the share of the migrants of the same age group will be as follows:

$$D_{ci} = D_{di} \cdot AK_{vi} \cdot AK_{gi}. \quad (4.20)$$

### Calculation of Function $f(Dc_i)$

Some fish species in the process of ontogenesis experience several migrations to the pelagic zone of the reservoir and, consequently, further migration from it. To estimate the total number of the migrants of various age groups, they need to be brought to the proportion of the migrants of a

certain fixed age. This proportion will be the ratio of the number of the migrants and the total number of the fish in the reservoir, taking into account the fish mortality:

$$Dc = \frac{Nuk - Nk}{Nuk} = 1 - \frac{Nk}{Nuk}, \quad (4.21)$$

where:  $Nuk$  is the assumed number of fish of the fixed age in the reservoir that are not likely to migrate, and  $Nk$  is the actual number of fish of the fixed age in the reservoir.

The number of fish of the certain age group can be determined by a number of laid (fertilized) roe and the mortality coefficient. For our purposes, let us select two components in the total number of fish mortalities, i.e., the mortality due to downstream migration and mortality due to other reasons that can be calculated by fish survival coefficient and does not depend on the first component. Then, the number of fish of the fixed age can be calculated by the following equation:

$$Nk = N_l \cdot E \cdot (1 - Dc), \quad (4.22)$$

where:  $N_l$  is the number of laid and fertilized roe;  $E$  – a number of fish that have survived, without taking into account their downstream migration;  $Dc$  is the number of fish that performed downstream migration from birth through the fixed age.

Then, using (4.22), the number of each specific age group can be calculated using the similar dependencies:

$$N_{i+1} = N_i \cdot E_i \cdot (1 - Dc_i), \quad (4.23)$$

where:  $N_{i+1}$  is the number of fish of the  $(i+1)$  age group in the beginning of their life;  $E_i$  is the number of the survived fish of the given age group;  $Dc_i$  is the number of migrating fish of the given age group, and this number for the fish outside the pelagic zone will be equal to 0.

Taking into account (4.23), we'll obtain the following for each age group:

$$\begin{aligned} N_2 &= N_1 \cdot E_1 \cdot (1 - Dc_1), \\ N_3 &= N_2 \cdot E_2 \cdot (1 - Dc_2) = N_1 \cdot E_1 \cdot E_2 \cdot (1 - Dc_1)(1 - Dc_2), \\ Nk &= N_1 \cdot E_1 \cdot E_2 \cdot \dots \cdot E_{k-1} \cdot (1 - Dc_1) \cdot (1 - Dc_2) \cdot \dots \cdot (1 - Dc_{k-1}). \end{aligned}$$

Ultimately, we'll obtain the following:

$$Nk = N_1 \cdot \Pi E_i \cdot \Pi(1 - Dc_i), \quad (4.24)$$

where  $\Pi$  is the symbol for the product of the members of the sequence.

To find the number of the fish surviving in the reservoir if we assume the absence of the downstream migration ( $Dc_i = 0$ ), according to (4.23), we'll obtain the following:

$$Nu_{i+1} = Nu_i \cdot E_i, \quad (4.25)$$

where:  $Nu$  is the assumed number of fish of the current age group in the reservoir with the assumption that they do not migrate, and  $i$  is the number of the age group.

Similar to (4.24), we'll obtain the following from (4.25):

$$Nuk = N_1 \cdot \Pi E_1. \quad (4.26)$$

Inserting the obtained values of  $Nk$  and  $Nuk$  into equation (4.21), we'll find the equation for calculating the number of the migrants for the fixed age group:

$$Dc = 1 - \frac{Nk}{Nuk} = 1 - \frac{N_1 \cdot \Pi E_1 \cdot \Pi(1 - Dc_i)}{N_1 \cdot \Pi E_i},$$

Making all necessary transformations, we'll obtain the following:

$$Dc = 1 - \Pi(1 - Dc_i). \quad (4.27)$$

The resulting equation for the model of downstream migration for the young fish from the reservoirs calculates the percentage of the migrants of the given age group out of the total number of the given fish species in the reservoir. This equation is as follows:

$$Dc = 1 - \Pi(1 - Dd_i \cdot Kv_i \cdot Kg_i), \quad (4.28)$$

where:  $Dd_i$  is the number of fish of  $i$ -age group in the HPP water intake influence zone out of the total number of fish in the reservoir, calculated by (4.15) – (4.17);  $Kv_i$  is the coefficient that shows the resistance of  $i$ -age group fish towards the vertical components of the water intake current calculated in Table 4-4;  $Kg_i$  is the coefficient that shows the resistance of  $i$ -age group fish towards the horizontal components of the water intake current in the water intake influence zone calculated by (4.19); and  $\Pi$  is the symbol for the product of the sequence members.

### Validation of the Model

Validation of the model has been performed with the data collected for the Ivan'kovskoe reservoir in 1979 – 1980 (Pavlov et al., 1984). The numbers of the migratory fish of various species have been calculated, based on year-round observations of the downstream migration through the HPP water intake and on the data on the number of various fish species in this reservoir provided by the Konakov Division of the State Research Fisheries Institute. The 1992 studies of the dynamics of the fish distribution in Ivan'kovskoe reservoir have allowed us to identify the number of fish ( $R$ ) permanently inhabiting the pelagic zone of the reservoir and the parameters of temporary migrations ( $T$ ) to the pelagic zone of the reservoir (see Table 4-1). To

identify the borders of the water discharge zone and calculate its area, as well as that of the littoral zone area, the navigational directions of the Ivan'kovskoe reservoir have been used. The calculation results and the actual data are provided in Table 4-4.

**Table 4-4 Percentage of fish migrating from Ivan'kovskoe Reservoir**

Value	Roach	Carp bream	Pikeperch	European perch	Bleak	Northern pike
Actual	0.06	1.50	15.20	0.81	3.60	0.00
Calculated	0.07	1.48	19.81	1.48	3.89	0.00
Calculation error, % of the actual data	23.33	1.27	30.30	82.35	8.00	0.00

As Table 4-4 shows, the majority of species illustrate a good compatibility between the actual and calculated data. However, there has been a significant error in modeling the downstream migration of European perch. As it is known (Konobeeva, 19836), the young European perch perform vertical movements in the pelagic zone. The range of those vertical movements and the average habitat depth (Pavlov et al., 1991a) are such that it does not stay at the water intake depth level all the time. Probably the neglect of these vertical movements have caused this significant error.

It should also be noted that this model contains some assumptions that have not been confirmed by the studies. It seems justifiable enough because, as of today, we do not have accurate quantitative data for many parameters of the model. Quantitatively, all the gaps in the existing model that require further thorough studies can be divided into the following three problem areas:

- patterns of fish behavior with changes of the hydraulic structure of the flow in the water intake zone;
- dynamics of seasonal redistribution of individual species in the ecological zones of the reservoirs, taking into account bays and coves with and without circulation; and
- ratios between the migrants in the tributaries and residents of the reservoirs.

If the first problem area is resolved, the patterns of fish behavior in the vicinity of the HPP water intake can be described in more detail and the more accurate mathematical description of the  $K_s$  value can be provided. The existing model describes these patterns through the coefficients that take into account the fish resistance towards the horizontal and vertical components of the water intake current. As a matter of fact, these coefficients only reflect the interactions between the fish and the water intake current, but they do not provide precise quantitative estimations.

The second problem area implies clarification of the parameters for dynamics of the fish redistribution in the ecological zones of the reservoir. If these problems are resolved, it will make it possible to achieve the following: estimate the time of migration into the open pelagic zone of

the reservoir and the time of staying in the pelagic zone for individual fish species; identify a number of such migrations within a life cycle; estimate the percentage of fish that go to the pelagic zone from the littoral and bathyal zones; and develop methods to account for non-homogenous distribution of fish in each ecological zone of the reservoir.

The third problem area is associated with the migration of fish that spawn in the tributaries and their distribution in the reservoir. The major goal of this problem area is to define the quantitative parameters that will provide the ratio of the migratory fish concentrations in the reservoir versus its tributaries.

All these problems can be solved if special complex studies and experiments are performed in specifically designed test sites in the reservoirs.



## Chapter 5 FISH INJURIES AND LOSSES FROM PASSAGE THROUGH HPP TURBINES

Fish passage through the turbine is the last and the most dangerous stage of the downstream migration from the reservoir. It always has consequences for the migrants and affects their further life. The fish that have gone through the turbine often have abnormal behavior and injuries, and sometimes they do not survive this passage. It may deplete the fish resources, especially for the diadromous fish because their downstream migration is vitally important for preserving the population. Therefore, this phenomenon has been under close attention of researchers.

It was over 60 years ago when those studies originated, in conjunction with construction of hydropower plants. In foreign countries, i.e., in the United States and some European countries, these studies have mostly been performed for Salmonidae sp. (Holmes, Morton 1939; Benson, 1954; Muir, 1959; Cramer, Oligher, 1964; Monten, 1985; and other authors). Thorough field-scale studies have been performed on fish passage through the turbines of existing HPPs. Simultaneously, special mock-up facilities have been developed where operational HPP conditions have been simulated to study the factors that affect potential fish injuries while passing through the turbines. All those studies have made it possible to find out how different kinds of turbines and the operation of these turbines affect the fish. The results of those complex studies have been described in a number of publications (Bell, 1981; Monten, 1985; Davies, 1988, Cada, 1990; Cada et al., 1997; and other authors).

In the Soviet Union, most studies were performed at existing HPPs. After passing through the turbines, the fish species were caught, examined, and their injuries were analyzed. The first studies of that kind were performed by P.V. Viktorov (1938) and M.I. Tikhij (1939). In their joint publication (Tikhij, Victorov, 1940), they summarized all the existing national and international experience on fish passage through HPP turbines. Between that time through the early 70's, no more studies of that kind were performed in the Soviet Union. In 1972 – 1975, such studies were performed only at Kapchagajskaya HPP (Nezdoly, Sazonov, 1974; Mitrofanov, Nezdoly, 1974; Nezdoly et al., 1975; Pavlov et al., 1981). At that time, the first Russian studies were made on how the pressure change affected the fish (Tsvetkov, Pavlov, Nezdoly, 1972). On the whole, there have been very few studies performed on the injuries following passage through the HPP turbines for the most common fish of the Russian reservoirs, i.e., Cyprinidae sp. and Percidae sp. (Tikhij, 1939; Volodin, 1958; Nezdoly et al., 1974, 1975; Pavlov et al., 1980, 1981, 1985, and other authors).

This chapter provides a review of the research results on fish passage through the turbines. The fish injury data have been given, design and operation of the existing turbines have been described, and various factors causing fish injuries and losses resulting from their passage through the turbines have been discussed.

## 5.1 Kinds of Fish Injuries on Passage Through the HPP

While estimating the fish losses at the HPP, usually a parameter such as mortality (the percentage of the fish killed divided by the total number of fish migrating through the turbine) is used. This value can be obtained by various methods, specifically: by putting marked fish species into the turbine and then catching them to compare their survival rate with that of the so called indication group of fish (Tikhij, Victorov, 1940; Monten, 1985; Bell, 1981, 1990; Mathur et al., 1996); by radiotelemetric measurements (Stier, Kynard, 1986); or, by estimating the percentage of the dead fish from the total number of the caught fish migrants. There are two types of death of the fish migrants after they pass through the turbines, i.e., immediate and delayed death. Immediate death means that the fish die while going through the turbine. The delayed death means that they may die some time after they pass through the turbine. The fish will die of the injuries or as the result of damage to their immune or other protective systems. In the latter case, the cause of their death will not be easily related to passage through the turbine. The damaged and stressed fish may be easily eaten by predators, and they are also more likely to catch a lethal infection or parasitism. Most performed studies have been dedicated to studying immediate death. Regarding the delayed fatalities, various injuries have been indicated by the authors but how they affect the further life of fishes has not been thoroughly studied yet (Cada et al., 1997). However, the type and degree of severity of injuries make it possible to evaluate the consequences. To give a general idea on the fish injuries, we have provided our research results on fish injuries and losses (immediate death) of the migrants. Fish injuries have been observed at practically all HPPs. We have collected most information at Ivan'kovskaya, Kapchagajskaya, Ust'-Khantajskaya, Mostiste and Al. Stambolijski HPPs (Table 5-1). I would like to extend my special thanks to Dr. V.K. Nezdoly who has analyzed and grouped the fish injuries for Kapchagajskaya, Ivan'kovskaya and Mostiste HPPs.

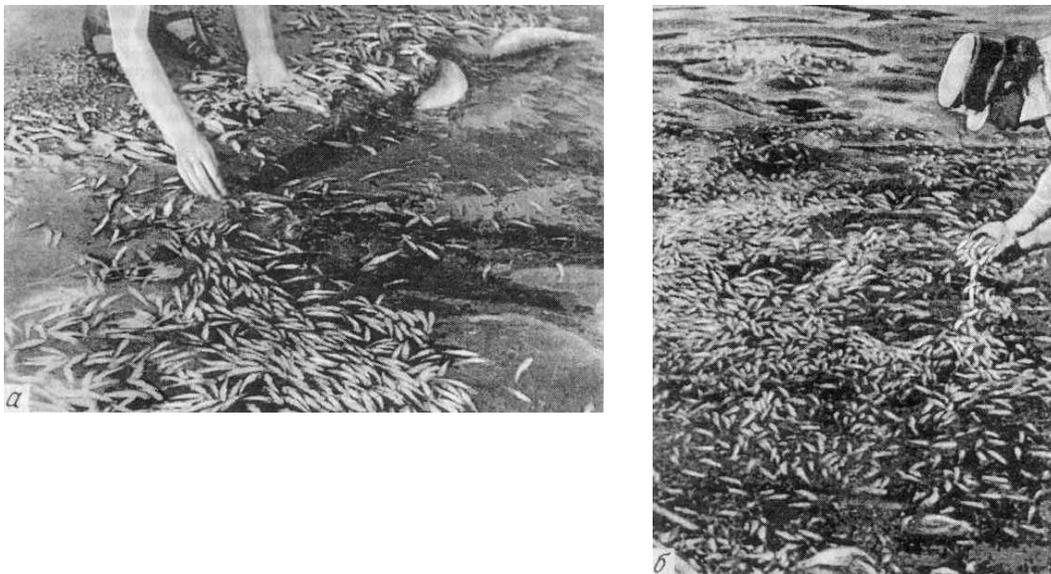
**Table 5-1 Collected data on fish injuries for studied HPPs**

	Ivan'kovskaya	Ust'- Khantajskaya	Kapchagajskaya	Mostiste	Al.Stambolijski
Fishes studied, specimen	2,414	314	364	166	318

After passing through the turbine, fish may have various injuries. First of all, their abnormal behavior in the tailwaters has been observed. Specifically, the fish did not react to visual, acoustic or hydraulic stimuli, there has been neither rheotaxis nor defensive or food search reactions observed. Some fishes did not have natural dorso-ventral orientation of their body. At Verkhne-Tulomskaya HPP, we have observed that salmon smolts started reacting to various stimuli only 30 minutes after they had passed through the turbine.

Special underwater research in the tailwaters has shown that many dead fishes with ruptured swim bladders had accumulated on the bottom. Most fishes with a closed swim bladder (pikeperch, European perch, ruffe and burbot) acquire a positive buoyancy after having passed the turbine and, being on the surface of the flow, they periodically tend to descend. The same situation has been observed at Ust'-Khantajskaya HPP with open swim bladder fishes, such as peled and sardine cisco. At Kapchagajskaya HPP, closed swim bladder fishes with a positive buoyancy have been observed at a large distance from the dam (about 70 km down), while the open swim bladder fishes have found the adequate depth of their migration 3 –5 km away from the dam. At Kapchagajskaya HPP, within two hours at the peak of their migration, 1,200 injured fry and up to 200 adult pikeperch fishes have been observed (Fig. 5.1). Since their orientation capability became lower than usual, they could be easily caught by predators (fish, birds, and mammals).

The visual observation of dead fish, as well as autopsy results, have indicated the following major types of injuries: bulging eyes (pikeperch, European perch: Fig. 5.2); scale damage (all fishes); cuts and lacerated wounds (fringebarbel sturgeon (*Acipenser nudiventris*), pikeperch, carp, carp bream, asp (*Aspius aspius*), roach, European eel, burbot, Northern pike, common whitefish (*Coregonus lavaretus lavaretus*), peled, sardine cisco, and European perch: Fig. 5.3); gas bubbles in the back muscles, inside the gills, fins and blood vessels (pikeperch and carp bream: Fig. 5.4); hemorrhages in the eyes, fins, muscles, abdominal cavities and brain (all species); swim bladder rupture (pikeperch, European perch, carp bream, European smelt and roach: Fig. 5.5); and irregular breathing (all species). Some dead fishes had discolored bodies (fringebarbel sturgeon *Acipenser nudiventris*), others, on the contrary, had pigmentation (Wels catfish and carp bream). The frequency of various injuries varies from species to species. However, hemorrhages into tissues and organs seem to be the most frequent injury (Table 5-2).



**Figure 5.1** Mass fish losses (a, б) during their migration from Kapchagajskoe reservoir (Pavlov et al., 1981)

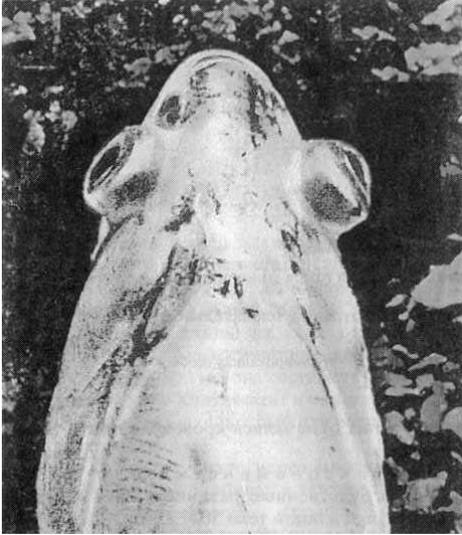


Figure 5.2 Pikeperch with bulging eyes after its passage through the turbine (Pavlov et al., 1981)

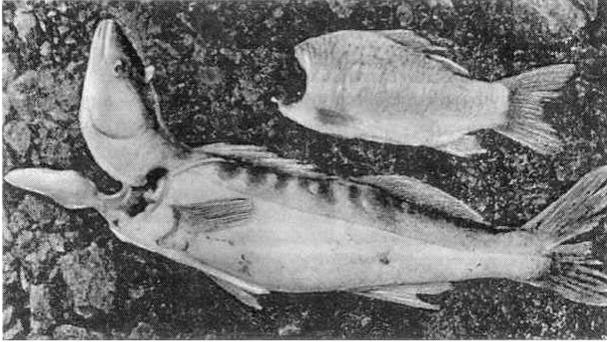


Figure 5.3 Fishes with lacerated wounds and cuts after having passed the HPP turbines (Pavlov et al., 1981)

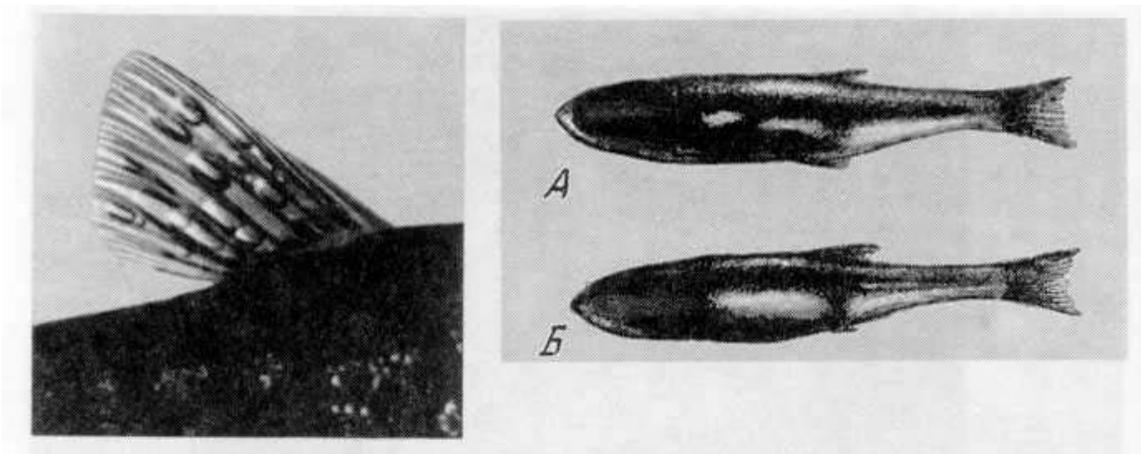


Figure 5.4 (left). Gas bubbles in the dorsal fin of minnow (*Phoxinus phoxinus*)

Figure 5.5 (right). Moderlieschen (*Leucaspius delineatus*) with swim bladder damage

A – intact swim bladder; B – damaged swim bladder

The scope of injuries also varied taxonomically. Specifically, at Ust'-Khantajskaya HPP, 88% of the *Coregonus sp.* with the body length of 50 – 150 mm were injured, while only 28% of the Percidae sp. were injured. The Cyprinidae sp. and Percidae sp. also had various percentage of injuries at Kapchagajskaya HPP, specifically: 88.9% of European perch were injured, pikeperch: 78.4%, and carp bream only 12.1%. At Ivan'kovskaya HPP, the Cyprinidae sp. had 9.0% rate of injury and Percidae sp. had 5.3 %.

Types of injuries strongly depend on the body size. Small fishes (Table 5-3) in Kapchagajskaya HPP mostly had swim bladder injuries, while large fishes, apart from swim bladder injuries, also had muscle ruptures, broken spine and scale damage.

**Table 5-2 Pikeperch and ruffe injury frequencies at Al. Stambolijski HPP (% of the total number of injured fish)**

Type of injury	Frequency, %
Swimbladder expansion or rupture	10
Hemorrhage in tissues or organs	92
Interior turned inside out	37
Eye bulging	40
Scratches and scale damage	13

**Table 5-3 Percentage of injured pikeperch at Kapchagajskaya HPP (% from the total number of the examined pikeperch)**

Body length, mm	Scale	Fins	Eyes	Gills	Swimbladder	Muscles	Interior
100 - 200	6.4	6.4	6.4	3.2	71.0	0	9.7
500 - 600	55.8	5.7	11.5	11.5	58.3	25.0	7.1

More injuries have been observed for larger fish sizes at some HPPs, while at other HPPs, there has been no correlation between increasing body size and a number of injuries. For example, at Ivan'kovskaya HPP, the number of killed or injured Cyprinidae grew with the 40 to 300 mm body size increase from 5.1 to 14.3%, respectively. Similarly, at Kapchagajskaya HPP, the 100 – 600 mm Percidae sp. body size increase resulted in the increase of the injured and killed fish from 51.6 to 71.4%. However, at Ivan'kovskaya HPP, there has been practically no difference in the number of *Coregonus sp.* injuries and losses for various body sizes.

The fish losses resulting from their downstream migration through HPP turbines, to a large extent, depend on the design and parameters of the turbine, as well as on the

hydraulic conditions of its operation (water pressure and flow rate, etc.). These factors determine the quantitative characteristics that cause the fish injuries and death.

To obtain a better understanding of why fish are injured or killed while passing through the HPP turbines, let us discuss the various turbine designs and identify the factors that affect fish endurance while migrating from the HPP head race to the tail race.

## 5.2 Types of Turbine Designs and Factors Affecting Fish Injuries and Death at HPP

The HPP turbine structure consists of the water intake, water receiving pipe and the hydraulic turbine with the draft tube (Fig. 5.6). The HPP gatewells are usually installed in the water, and, in some cases, they may be installed near the bottom. Usually, they are covered with the debris collection screen (trash rack) and equipped with the locks of various applications (emergency, maintenance, etc.).

The water is supplied to the turbine by means of the open or spiral chamber. As a rule, the spiral chamber is connected with the gatewell by a special curved cone-shaped water pipe with a lateral (annular) water feed to the turbine.

The hydraulic turbine is a high-speed system that converts the water flow energy to, first, the mechanical energy for rotating the generator rotor and, then, resulting from its rotation, to electrical energy. In accordance with the operation principle, the turbines are divided into impulse and reaction turbines.

Impulse turbines only use kinetic energy of the flow that goes from the nozzle of the pressure pipeline to one or several turbine blades, making the turbine wheel (runner) rotate.

In the reaction turbines, the water flow simultaneously goes through all inter-blade channels of the turbine runner, and, therefore, all the blades receive the flow energy. Curvilinear shape of the channels changes the direction of the flow, thereby creating the centrifugal forces that affect the turbine wheel. Thus, the action of the flow in the reaction turbines consists of the reaction pressure, resulting from the current velocity increase, and centrifugal forces, resulting from the change of the flow direction in the inter-blade channels. The reaction turbines are considered to be the most economical and they are very widely applied at the HPPs. Therefore, the further narration will only refer to the reaction turbines.

The reaction turbine (Fig. 5.7) consists of the three major components: the throttle (wicket gate), runner and the draft tube. The wicket gate consists of two rings and the blades between them that can be rotated by a special device, blocking or providing the water access to the turbine and, therefore, adjusting the water flow rate to the turbine.

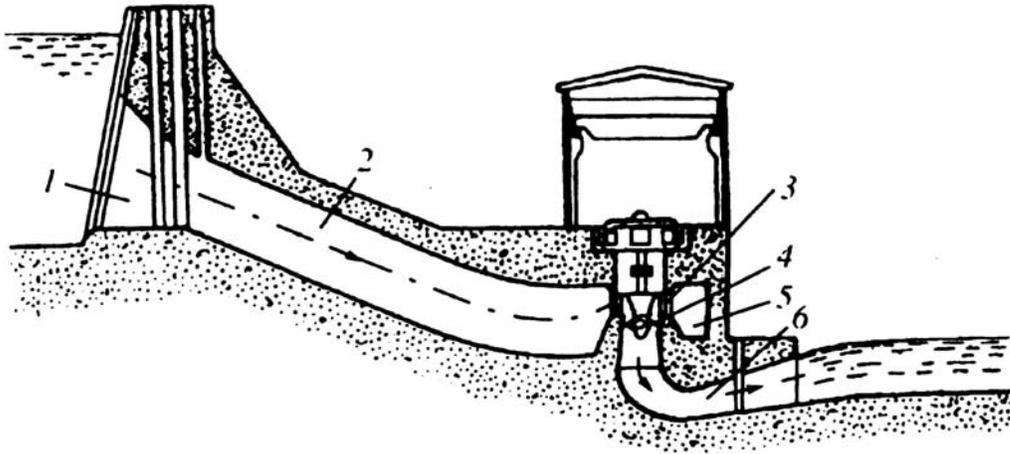


Figure 5.6 Vertical cross section of penstock

1 – gatewell; 2 – water feeding channel; 3 – wicket gate; 4 – turbine runner; 5 – spiral chamber; 6 – draft tube

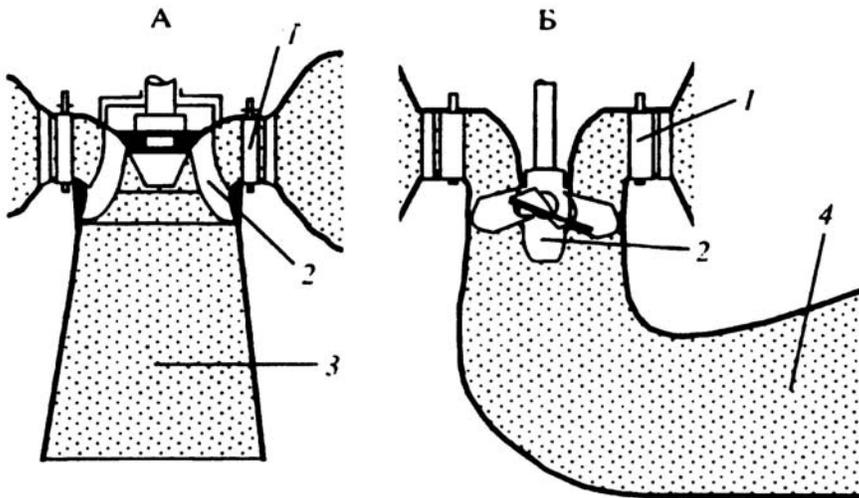
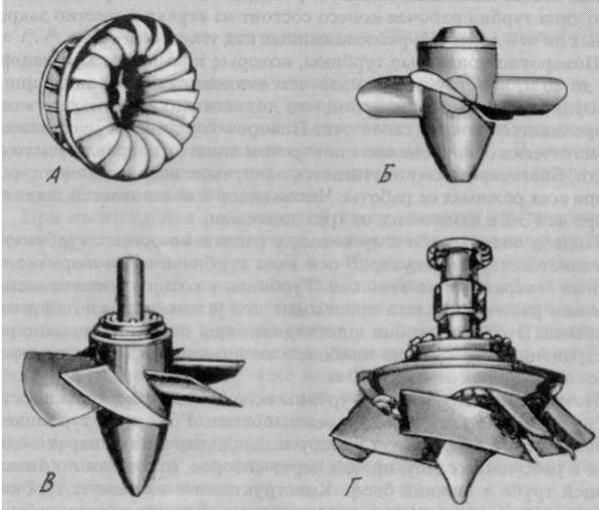


Figure 5.7 Vertical cross section of Francis type turbine (A) and Kaplan type turbine (B)

1 – wicket gate, 2 – runner; 3 – direct flow draft tube; 4 – curved cone draft tube



**Figure 5.8 Types of reaction turbines**

A – Francis turbines; Б – Kaplan; Б – Propeller Type; Г – Diagonal

The runner of the turbine is installed downstream from the wicket gate. Therefore, the water flow, going through it, goes directly to the inter-blade channels. The water is removed from the runner by the draft tube. Since the draft tube has a curved cone shape, it provides additional rarefaction underneath the runner, thereby applying the kinetic energy of the flow more efficiently. The outlet of the draft tube is always located on the level of the tail race.

According to the design features, there are the following types of reaction turbines (Fig. 5.8): Francis turbines, diagonal turbines, propeller type turbines and Kaplan turbines.

Francis turbines are most commonly used at heads of 40 to 500 m. They consist of the shaft and curved runner blades along the shaft axis. The curved runner blades form inter-blade cavities. The runner blades are covered from the top and have an annular configuration below.

The propeller type turbines are used for heads of 2 – 70 m. They differ from the Francis type turbines by the runner design that provides a better reactivity and higher speed. The runner of the propeller type turbines has a shaft and tightly fixed blades that are installed at a fixed angle to the shaft axis.

Kaplan turbines are used at heads of 5 – 80 m. They do not considerably differ from the propeller type turbines. The only significant difference is that the runner blades can rotate along their axis. The blades rotate automatically, together with the blades of the wicket gate, thereby providing the optimal efficiency of the turbine for all its operational modes. A number of rotating blades varies from 3 to 8, depending on the HPP head.

The water feed to the runner is perpendicular to the turbine shaft axis in Francis type turbines and parallel to this axis in Kaplan type turbines. The turbines with the water feed to the runner blades at an angle are defined as diagonal turbines. This type of turbines has

become common recently because they are the most economical and can be used with the heads of 40 to 120 m.

Regardless of the turbine type, the water with the migratory fish goes from the reservoir to the HPP gatewell and then, through the spiral chamber and the wicket gates, to the runner blades and, through the draft tube, to the tail race. The design components of the turbine, high current velocities and rotation of the runner blades create conditions that may be very harmful for fish. While migrating from headwaters to the tailwaters, the following factors may cause fish injuries and losses:

pressure change;  
turbulence and shear forces, resulting from the flow velocity and direction changes;  
cavitation due to decompression after the fish passes the runner blades;  
contact with mechanical components of the turbine.

### 5.3 Pressure Change as One of the Causes of Fish Loss and Injuries at Turbine Passage

Various authors use various starting points for measuring how pressure changes would affect the fish. Some authors use absolute pressure, others use excess (or gauge) pressure. In many cases, the discrepancy in the approaches makes it difficult to compare and evaluate the results. These pressure values are correlated with the atmospheric pressure in the following way:

$$P = P_a + P_i,$$

where:  $P$ ,  $P_a$  and  $P_i$  are the absolute, atmospheric and excess pressures, respectively.

The absolute pressure is measured from the absolute zero, and the excess (manometric) pressure is measured from the atmospheric pressure. The pressure below atmospheric pressure is called vacuum, and it has the negative values (Fig. 5.9). When pressure is mentioned in this Section, it mostly refers to the absolute pressure.

When the fish passes through the turbine, the hydrostatic pressure changes, as well as the pressure caused by changes in current velocity in the HPP turbine channels. The change of hydrostatic pressure is related to the change of the depth level for the fish. The pressure change in the HPP channels is caused by the flow velocity change, i.e., the flow velocity increase always causes the pressure drop or vice versa (Fig. 5.10). Thus, the fish exposure to pressure changes depends on what depth the fish is located (adaptation depth or pressure) prior to getting into the turbine and after leaving the turbine (possible parameters of this pressure are given in Fig. 5.10 by a dotted line), and also on the hydraulic conditions in the turbine (a solid line in Fig. 5.10).

If the surface-dwelling fish goes to the deeper levels, it will be exposed to a higher pressure. If the fish is adapted to high pressures and is taken to the gateway from deep waters, it, on the contrary, will be exposed to a decrease of the hydrostatic pressure.

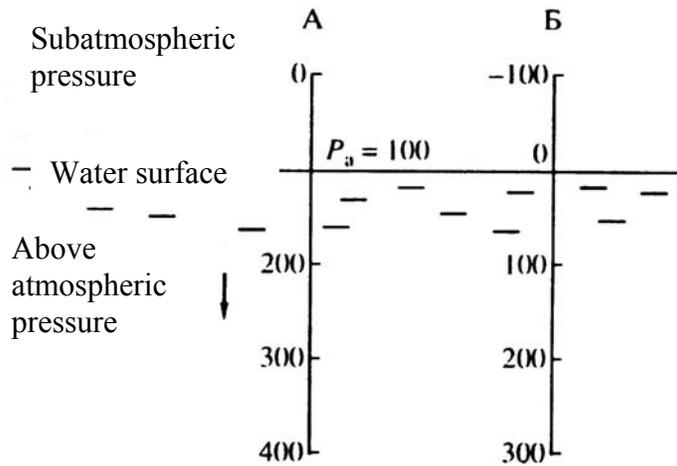


Figure 5.9 Correlation between the absolute (A) and excess Pressure (B) for the atmospheric pressure  $P_a = 100$  kPa.

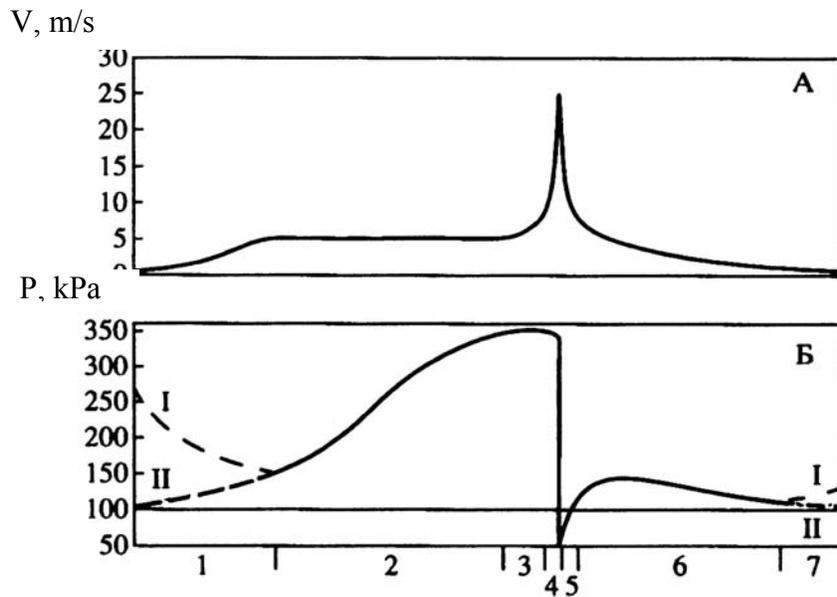


Figure 5.10 Current velocity (A) and absolute pressure (B) changes for bottom-adapted (I) and surface-dwelling fish (II) in various areas of penstock

1 – headwaters and entrance to the penstock; 2 - water feeding channel; 3 – spiral chamber; 4 – wicket gate; 5 – turbine runner; 6 – draft tube; 7 – tail race (ref.: Monten, 1985)

The current velocity goes up and the pressure goes down in the spiral chamber and in the wicket gate. In that area of the turbine, the fish begins to experience a considerable pressure drop, and after they pass the runner, the pressure may go below atmospheric pressure (vacuum) and the bottom-adapted fish will be exposed to significant decompression. The normal hydrostatic pressures will be restored in the draft tube and tailwaters. Depending on where the fish leaves the draft tube, it will be exposed to various pressures, ranging from atmospheric on the water surface to higher pressures if leaving it closer to the bottom.

The pressure change in the runner blades (Fig. 5.11) depends on the head and can be estimated by the following equation:

$$\Delta P = P_1 - P_2 = \rho \cdot g(H - h - z) - 0.5\rho(V_1^2 - V_2^2),$$

where:  $P_1$  and  $P_2$  are the pressure values, in front of and behind the runner blades;  $H$  – dam head (difference in headwaters and tailwaters depths);  $h$  is the head loss in the penstock;  $z$  is the difference between the entrance and exit of the runner (runner height);  $V_1$  and  $V_2$  are the velocity currents in the inlet and outlet of the runner, respectively;  $\rho$  is the water density, and  $g$  is the acceleration of gravity.

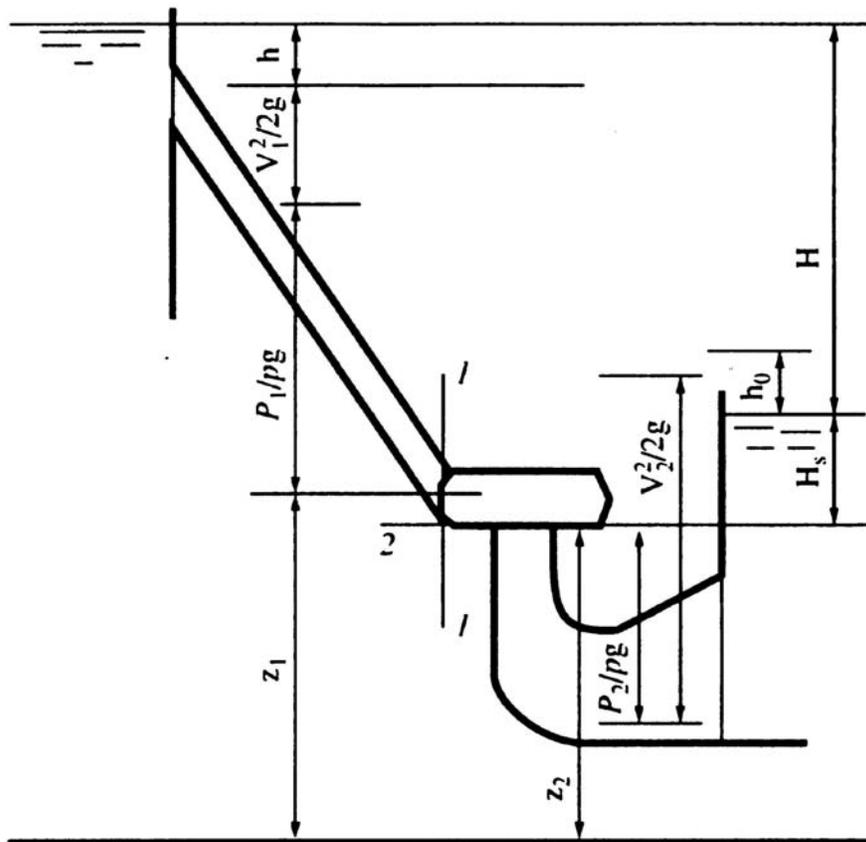


Figure 5.11 Estimation of water flow parameters in the HPP penstock

With the head increase, the range of the pressure change in the area that equals the height of the turbine runner increases. This pressure change may be considered one of the causes of fish injuries.

The reduction in pressure below the runner may also cause fish losses (Fig. 5.11). Its value can be estimated by the following equation:

$$P_2 = P_a + \rho \cdot g(H_s + h_0) - 0.5\rho V_2^2,$$

where:  $H_2$  is the difference between the water level in the tail race and the location of the turbine blades;  $h_0$  is the head loss in the draft tube. The higher the runner is located above the tailwaters, the higher negative pressure  $H_s$  and pressure decrease  $P_2$  will be reached. Cramer and Oligher (1960) think that the fish losses grow if the pressure in the draft tube is subatmospheric. According to their data, the fish losses reached 100% at Cushman HPP-2 dam when the water level in the tail race went down and the pressure behind the runner dropped.

The hydrostatic pressure and the pressure associated with the change of the flow velocity affect the fish in a similar way, although they are of different nature. These two kinds of pressure will only differ in intensity that will depend on the speed of the fish movement during various stages of their downstream migration. For example, if the fish gradually change the depth level in the vicinity of the HPP gateway due to descending and ascending flows, the pressure change intensity will be low and it is not very likely to cause any harm to the migrants. If the fish are in the penstock, the pressure will be changing rapidly and the rapid pressure change will be especially harmful in the spiral chamber and in the turbine runner.

When the fish migrate through the turbine, the pressure that affects them is closely related to the pressure to which the fish are adapted. Therefore, its pressure value will vary for surface-dwelling and bottom-adapted fish. Specifically, the hydrostatic pressure for the surface-dwelling fish when they leave the draft tube in the tailwaters will have little or no difference from the pressure they have been adapted to. But for the bottom-adapted fish, the pressure in the tailwaters will be much lower than they are adapted to. For them, this pressure change will be equivalent to going upward to the surface. The maximum possible pressure change for the migrants cannot exceed the pressure value associated with the headwaters depth. The time of passing the turbine depends on the length of the penstock and the flow velocity. The fish may pass it very fast, for example, in as little as 15 seconds (Cada, 1990). The time of entrainment in the turbine, as well as the maximum hydrostatic pressure, affect the maximum intensity of the pressure changes. It should be noted that some fish acquire positive buoyancy in the tailwaters of some HPPs (Kapchagajskaya, Ust'-Khantajskaya and some others), and it is believed to be caused by the hydrostatic pressure change. The positive buoyancy occurs because a fish entrained in the water intake from greater depth cannot return there from the tailwaters because the tailwaters are not as deep as the headwaters. Therefore, the fish will have to adapt to the new conditions.

If the hydrostatic pressure only affects the bottom-adapted fish, the turbine induced pressure change affects all fish. However, even in this case, the pressure change will mostly affect bottom-adapted fish because they will experience the maximum pressure drop. For a few tenths of a second, the fish migrants will experience a pressure drop from the positive pressure to subatmospheric (Monten, 1985; Dadswell et al., 1986; Wapora, 1987). The intensity of the pressure drop is very high below the runner, it is much higher than the hydrostatic pressure change. Therefore, the turbine-induced pressure change will be the most harmful for the fish migrants. For example, at Cushman HPP (head  $H = 135$  m, flow rate  $Q = 22 \text{ m}^3/\text{sec}$ ), the  $\Delta P$  value in the runner is 766.8 kPa and the time ( $t$ ) of the turbine entrainment for the fish does not exceed 0.07 sec (Bell, 1990). At such mode of the turbine operation, the pressure change rate ( $\Delta P/t$ ) equals to 10,954.3 kPa/sec. At Shasta HPP ( $H = 120$  m,  $Q = 95 \text{ m}^3/\text{sec}$ ) these parameters are much lower, i.e.:  $\Delta P = 645$  kPa,  $t = 0.16$  sec, and  $\Delta P/t = 4,031.3$  kPa/sec. Consequently, the fish fatalities at Shasta HPP are 15% lower than at Cushman HPP.

Our estimations show that the Nizhne-Tulomskaya HPP has the turbine induced pressure change of 87 kPa and this pressure change rate is 255 kPa/sec. The same parameters for the Verkhne-Tulomskaya HPP are 518 kPa and 2,460 kPa/sec, respectively. The 1996 – 1997 studies indicated that 10 – 18 cm long smelt\* and sardine cisco species went through Nizhne-Tulomskaya HPP without any visible damage, but they acquired some typical pressure change-induced lethal injuries while migrating through Verkhne-Tulomskaya HPP, i.e., bulging eyes, hemorrhages in fins, gills and abdominal cavity. Salmon\* smolts migrated through Nizhne-Tulomskaya HPP without damage and about 15% of these species were killed while migrating through Verkhne-Tulomskaya HPP.

The severity of injuries depends on the absolute pressure values and pressure change rate, as well as on a capability to tolerate pressure changes.

Since the body fluids and tissues are not likely to be severely compressed, pressure will only affect gas filled cavities and, primarily, the swim bladder. For example, in the water temperature range of 0 - 25°C and the pressure increase from 100 to 1,100 kPa, the fish body tissues will only be reduced by 3 – 4% (Newton, Kennedy, 1965). However, the gas volume in the body will significantly change. The pressure increase will cause the gas volume decrease and vice versa. The faster a fish can change (compensate) the gas volume in the swim bladder, relieving the stress on its surface, the less severe effect the pressure will have.

The physiological reaction on pressure change compensation will depend on how various fish species are capable of filling or emptying their swim bladder. Depending on this ability, the fish can be divided into open swim bladder and closed swim bladder species.

A swim bladder of open swim bladder fishes is connected with their digestive system. It allows them to take the air from the water surface if the pressure increases and, sending it through the esophagus and the air channel, fill the swim bladder, compensating for the

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\* Note of the translator: Here and below the scientific names have not been provided in the original text.

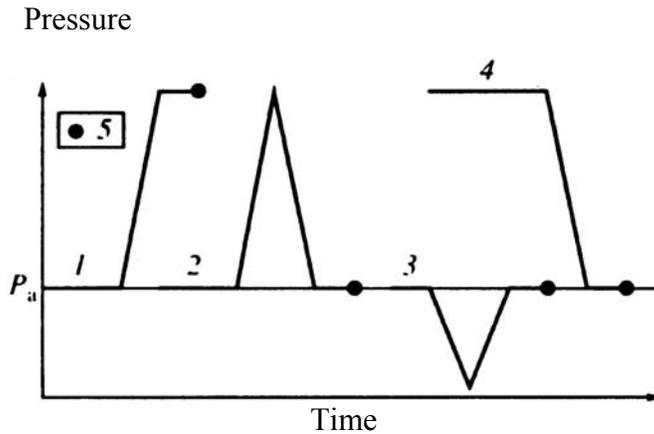
external pressure increase (Evans, Damant, 1928; Jacobs, 1934; Franz, 1937; Bishai, 1961; Brawn, 1962; Qutob, 1962; Tsvetkov, 1974). If the pressure goes down (decompression), they can easily and rapidly equalize the pressure, releasing excess gas through the air channel or, like Clupeiformes, through a hole located near the anal fin (Franz, 1937; Braw, 1962; Nikolsky, 1964; Marshall, 1965; Fahlen, 1967; Tsvetkov et al., 1972; Blaxter, 1980; Ephanov et al., 1986). The reaction to remove the excess gas from the swim bladder is characteristic of Clupeidae species for a 6.4% pressure drop, tench for the 4.35 – 7.48 kPa pressure drop (Guyenot, 1909) and minnow for a pressure drop of 6.8 kPa (Kokas, 1932).

A swim bladder of closed swim bladder fishes has secretory and resorption parts. Gas secretion into the bladder is their physiological mechanism of compression (Evans, Damant, 1928; Brown, 1939; Fange, 1953; Scholander, 1954; Jones, 1957; McCutcheon, 1962; Alexander, 1966; Tsvetkov et al., 1972; tsvetkov, 1974). Closed swim bladder fish larvae have an open swim bladder with an air channel (Hadley et al., 1987). Those larvae are likely to rapidly change the pressure in their swim bladders, like open bladder fishes, by releasing the excess gas or taking it from the water surface through the air channel (Tsvetkov et al., 1989). However, the air channel closes at late fry and adult stage, and it takes much longer for closed swim bladder fish to provide gas regulation, thereby making them more vulnerable to pressure changes. The speed of closed swim bladder fish gas regulation varies from species to species. For example, the adaptation of *Tilapia* to 100 kPa takes 5 – 12 hours (Bishai, 1961), ten-spined stickleback – 22 – 24 hours, *Symphodus mediterraneus* – over 48 hours, *Mugil cephalus* – 18 hours (Tsvetkov, 1974), European perch – 23 – 27 hours (Tsvetkov et al., 1972). With decompression, the normal pressure in the swim bladder is restored by discharging excess gas into blood and releasing it through the gills (Fange, 1945, 1953; Jones, 1951). These processes go much faster than secretory processes. For example, one volume of the European perch swim bladder can resorb within 12 hours (Jones, 1951), of *Tilapia* – within 5 hours (Bishai, 1961).

Taking into account the capabilities of the swim bladder, we may assume that it is very difficult for closed swim bladder fish to adjust to pressure changes. If high pressures are applied, their swim bladder will shrink, if low pressures are applied, their swim bladders will expand, causing frequent ruptures. For example, if the bottom-adapted European perch is quickly taken to the surface, reducing the pressure by a factor of 2.5, its swim bladder will not tolerate the expansion and will rupture (Jones, 1952). Open swim bladder fish have better capabilities to adjust the gas volume in their swim bladders. If the pressure goes down and the swim bladder expands, they can easily release excess gas from the swim bladder, adjusting it to the lower pressure conditions. However, with a very rapid pressure change, they are not always capable of releasing the required amount of the excess gas in time, thereby causing its rupture.

Apart from the injuries caused by the swim bladder volume change due to a rapid pressure drop, a so called “gas disease” may also occur. The gas disease has been described in literature (Marsh, Corham, 1905; Henly, 1952; Bishai, 1960). It is caused by rapid decompression and is characterized by gas bubble (primarily nitrogen) release in

blood and tissues. The gas bubble may result in clogging the blood vessels, thereby causing their rupture or poor blood circulation.



**Figure 5.12 Pressure changes in the experiments**

1 – Compression; 2 – Compression followed by decompression; 3 Surface-dwelling fish decompression; 4 –Bottom-adapted fish decompression ; 5 – Pressure values when the data have been obtained

Most studies on how pressure affects the turbine-entrained fish describe bench-scale or lab-scale experiments. During those experiments, the fish were exposed to various pressure ranges. The pressure change modes were, in some cases, more rigid than in the HPP conditions, but the pressure change intensity was not as high as under the actual HPP conditions. Below are some of these experimental results obtained for four typical pressure change modes, i.e., compression, compression followed by decompression, surface-dwelling fish decompression, and bottom-adapted fish decompression (Fig. 5.12).

### **Compression**

Many experiments have been performed to study how high pressures affect fish. Harvey (1963) exposed sockeye salmon (*Oncorhynchus nerka*) smolts and fry to a very high pressure (2,064 kPa), but failed to obtain any well-defined value for their fatalities. Nishiyama (1965) indicates that, at pressures of about 2,500 kPa, the fish has convulsive movements and difficulty in breathing. Quasin et al. (1963) have reported a loss of orientation at such pressures. There are many data obtained by other authors (Muir, 1959; Calderwood, 1945; Lucas, 1962, and others) that indicate a good tolerance of fish towards high pressures. All of them state that even a significant pressure increase may change the fish behavior, but is not likely to be fatal in the short run.

### **Compression Followed by Decompression**

Some studies first increase pressure and then reduced it down to the original value (Fig. 5.13). This pressure change mode is characteristic of the beginning of the penstock. It will be typical for surface-dwelling fish that are transferred downward and then again upward.

Some publications (Calderwood, 1945; Lucas, 1962; Gordon, 1970) indicate that slow compression and decompression do not cause any significant harm to *Oncorhynchus sp.* and Atlantic salmon (*Salmo salar*).

Rowley (1955), studying the behavior of rainbow trout (*Oncorhynchus mykiss*) fry, increased the pressure from atmospheric to 1,276 kPa within less than one minute and then immediately restored the original pressure. When the pressure went up, the fish came to a standstill and remained immobile. However, as soon as the pressure was back to normal, they restored their usual activity and no fatalities were observed. Foye and Scott (1965) did not observe any fatalities either, experimenting on six fresh water species: *Morone saxatilis*, yellow perch (*Perca flavescens*), *Semotilus*, *Cymatogaster aggregata aggregata*, sea trout (*Salmo trutta*) and Atlantic salmon (*Salmo salar*), exposing them to an instantaneous pressure increase up to 1,964 kPa and then decompressing them down to atmospheric pressure within a 10-minute period.

Lampert (1976) used whitefish (*Coregonus sp.*) and common carp (*Cyprinus carpio*) fry in his experiments. He increased the pressure up to 500 kPa and maintained it for 10 minutes for adaptation and then reduced it down to the atmospheric pressure. No fatalities were observed. It may be explained by the short period for adaptation to a high pressure. Similar data have been obtained by Fedyaj (1981) when he maintained 300 – 900 kPa for 10 minutes and then reduced it down to the atmospheric pressure for young blue bream (*Abramis ballerus*) and adult *Gasterosteus aculeatus*. Turnpenny et al. (1992) increased the pressure to 405 kPa within a 5-second period and exposed *Clupea harengus*, American shad (*Alosa sapidissima*), Atlantic salmon (*Salmo salar*), sea trout (*Salmo trutta*), *Oncorhynchus mykiss*, yellow perch (*Perca flavescens*), and American eel (*Anguilla rostrata*) to those conditions for 15 seconds, then putting pressure back to normal. No injuries were observed.

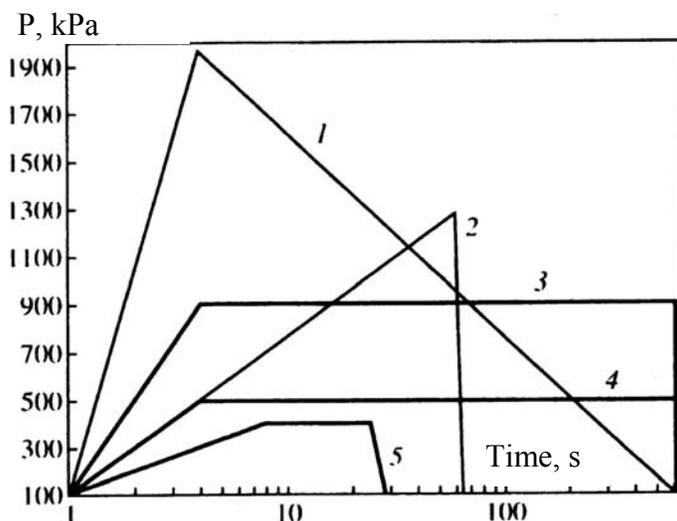


Figure 5.13 Pressure change modes in the experiments (quoted from the literature)

1 – Foye, Scott, 1965; 2 – Rowley, 1955, 3 – Fedyaj, 1981; 4 – Lampert, 1976; 5 – Turnpenny et al., 1992

The fish tolerance to such pressure modes can be explained by the fact that they do not have enough time to adapt to high pressures and, consequently, during decompression, they do not undergo any physiological changes in their tissues or organs. Thus, a conclusion can be made that rapid compression with subsequent rapid decompression down to the atmospheric pressure does not cause any fish fatalities.

### Surface-Dwelling Fish Decompression

Rapid decompression to subatmospheric values followed by a rapid compression (Fig. 5.14) has been associated with fish fatalities. The fatalities in this case will depend on the fish adaptation depth (their habitat depth). Therefore, first surface-dwelling fish decompression will be described, i.e., the fish that are adapted to the atmospheric pressure.

Hogan (1941) was one of the first scientists who exposed fresh water fish to various decompression modes. First he adapted the fish to atmospheric pressure and then reduced it to 17 kPa within 15 seconds. Open swim bladder fishes, i.e., minnow (*Phoxinus phoxinus*), common carp (*Cyprinus carpio*) and longnose gar (*Lepisosteus osseus*) tolerated this pressure change better than closed swim bladder fishes, such as *Lepomis macrochirus*, white crappie (*Pomoxis sp.*) and largemouth bass (*Micropterus salmoides*), most of which were killed. Besides, the longer they were exposed to decompression, the higher was the mortality rate. None of the open swim bladder fishes was killed. During decompression, they released excess gas from the swim bladder through the pneumatic duct. Thus, open swim bladder fish resist decompression much better than closed swim bladder fish.

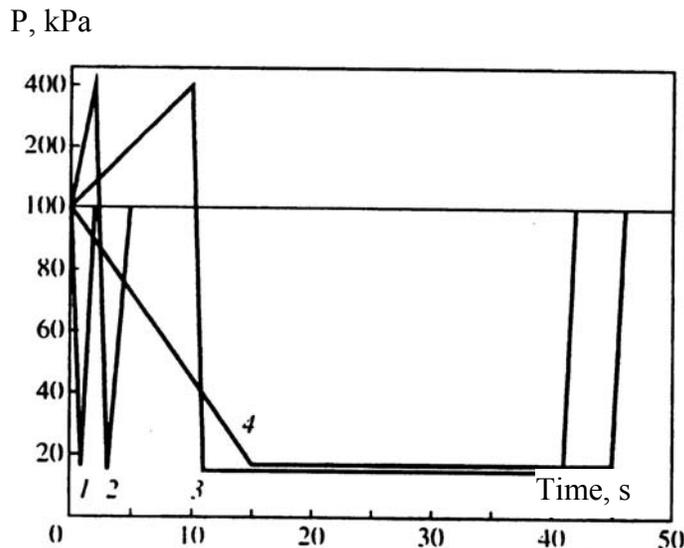


Figure 5.14 Pressure change modes in the experiments (quoted from literature)

1 – Harvey, 1963; 2 – Turnpenny et al., 1992; 3 – Turnpenny et al., 1992; 4 – Hogan, 1941

Turnpenny et al. (1992) increased the pressure to 405 kPa during 10 seconds and then dropped it to subatmospheric within 0.1 seconds (15 kPa). The fish were exposed to subatmospheric pressure for 30 seconds and then returned to atmospheric pressure. No injuries were observed under these conditions. However, when the same pressure change mode was applied much faster, i.e., within 5 seconds, 10% of the fish (salmon\*, sea trout and *Oncorhynchus mykiss*) suffered swim bladder ruptures. *Clupea harengus* did not have any injuries. The authors explained it by a capability of an open swim bladder fish to quickly release the excess gas from their swim bladder during decompression. However, even open swim bladder fish (Turnpenny et al., 1992) may suffer from swim bladder rupture, resulting from a very rapid and significant decompression because the swim bladder increase will exceed the capability of the excess gas release.

Harvey (1963) exposed sockeye salmon (*Oncorhynchus nerka*) smolts to a very rapid decompression (52 kPa/sec) that caused some fatalities. With pressure below 67 kPa, 2% of the fish died. He discovered that the speed of decompression significantly affected the fish mortality rate. Gradual pressure decrease down to 16.5 kPa did not hurt the fish. Beyond that, he exposed the surface-dwelling fish to a drastic pressure increase followed by a rapid decompression, resulting in some fatalities.

All these experiments show that rapid decompression may cause surface-dwelling fish losses, resulting from swim bladder ruptures. The fish losses directly depend on the degree of decompression and the speed of the pressure change. The more drastic and the faster the decompression is, the higher is the mortality rate. Closed swim bladder fish suffer more from decompression than open swim bladder fish because the former are not capable of quickly adjusting the gas pressure in their swim bladder.

### **Bottom Adapted Fish Decompression**

Harvey (1963) rapidly (52 kPa/sec) reduced pressure down to 16.5 kPa for fish adapted to 2,000 kPa. Under these conditions, the sockeye salmon (*Oncorhynchus nerka*) smolt fatalities were 35%, resulting from the gas bubble disease that mostly affected heart or abdominal aorta.

Fedyaj (1981) experimented on rapid (90 kPa/sec) pressure drops from 300, 700 and 900 kPa down to 20 kPa, resulting in 90% fatalities of Northern pike and roach larvae and blue bream (*Abramis ballerus*) fry. The fish losses were mostly related to gas bubble disease.

Therefore, rapid decompression in the turbine runner area may cause the bottom adapted fish losses, resulting in gas bubble disease.

Bottom-adapted fish also experience change of the hydrostatic pressure because they are returned to much more shallow water in the tail race than in the head race. Studies of this pressure drop have been performed by Russian scientists (Tsvetkov et al., 1972; Nezdoly, Sazonov, 1974; Pavlov et al., 1981). Those studies showed that, after a long adaptation to a high pressure (200 – 700 kPa) and its rapid (10 – 600 kPa/sec) drop down to

atmospheric pressure, the fish behavior changed. As a rule, the fish did not have a normal dorso-ventral body position near the water surface and most of the fish had decreased reactions to external stimuli. Apart from the behavioral changes, some pressure-induced injuries have been detected (Pavlov et al., 1981), specifically, bulging eyes (especially for Percidae sp.) and swim bladder rupture, from the ventral side for Cyprinidae sp. and gas gland for Percidae sp. The digestive system had some conglomerations of bubbles, regardless of the swim bladder condition. The bubbles could have been originated from discharge of excess gas from the swim bladder or breathing in gas during compression. The blood vessels in the foundations of the fins were expanded and, in most cases, they were ruptured. Some internal hemorrhages have also been detected. Eyes, gills and gill mucous cavities had gas bubbles, and, in some cases, huge conglomerations of bubbles generating foam chunks have been observed.

The fish losses in the experiments varied, depending on a particular kind of species and size (Pavlov et al., 1981). For example, with an instantaneous 300 kPa pressure change for the 50 – 100 mm long fishes the mortality rates were as follows: Balkhash perch (*Perca schrenki*) – 9%, topmouth minnow (*Pseudorasbora parva*) – 14%, carp (*Cyprinus carpio*) – 70%, *Ctenopharingodon idella* – 80%. For young pikeperch 10 – 19 mm long, only 6% of all the species died, and there have been no *Rhinogobius brunneus* fatalities observed. At the same time, young topmouth minnows 35 – 49 mm long had 42% fatalities with 300 kPa pressure change and only 42% fatalities for the species 50 - 75 mm long. Those experiments have shown that types of injuries and losses of fishes depend on both the genera and the age. It also depends on the range of the pressure drop and intensity of its change. For example, for the young 75 – 90 mm carp there were 50% losses at 250 kPa/sec pressure change, but no losses at 20 kPa/sec pressure change.

Feathers and Knable (1983) conducted similar studies. They adapted largemouth bass (*Micropoterus salmoides*) to pressures of 191, 280 and 369 kPa and then rapidly reduced it to the atmospheric pressure. The fish losses in the experiments were directly related to the decompression values. With the adaptation pressure of 191 kPa the fatalities were 25%, while, with the adaptation pressure of 369 kPa, the fatalities were 46%. It should also be noted that, with a high initial (adaptation) pressure, most fish died during the first hour, while, with the lower decompression values, the fish died during the first five days. The causes for death of fish adapted to various pressure values were different. At the minimum range decompression (191 kPa), the fish died due to damage of the respiratory system or the stress resulting from their strong positive buoyancy. The highest range decompression (369 kPa) caused gas bubble disease, resulting in rupture of blood vessels and formation of large gas bubbles in the area of heart, gills or brain. The experiments have shown that even relatively small, but rapid, pressure drops may kill the fish.

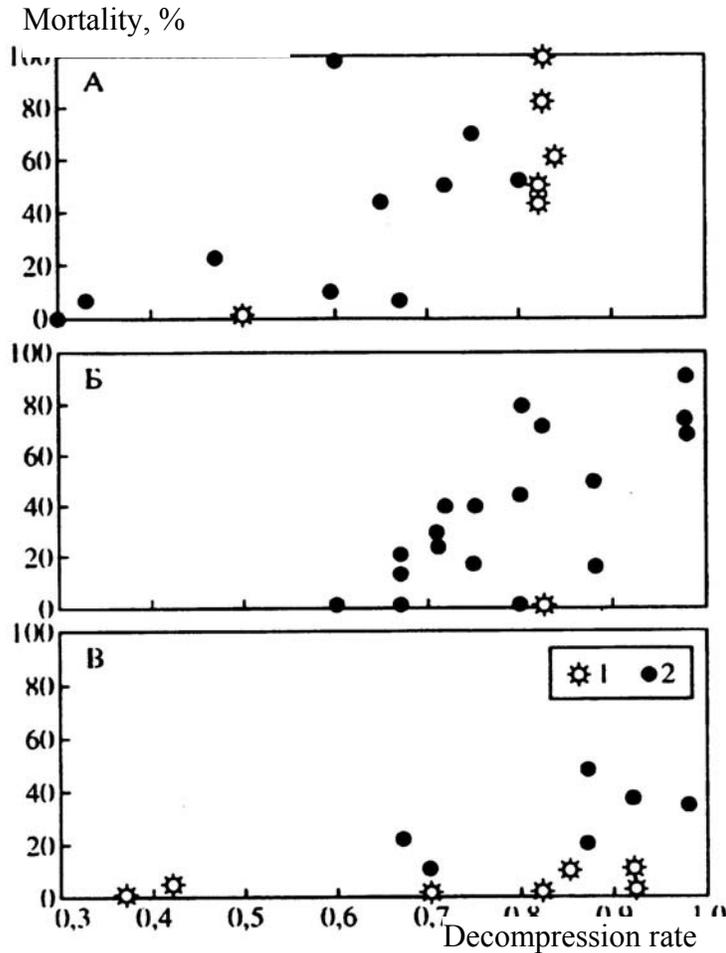


Figure 5.15 Fish losses as a function of decompression rate (quoted from various literature)

A – Percidae sp., Б – Cyprinidae sp., B – Salmonidae sp. Fish adaptation: 1 – surface, 2 - bottom

The available literature data on pressure change-induced fatalities have been reviewed and summarized in Fig. 5.15 where the fish fatalities are shown as a function of decompression rate  $D = (P_1 - P_2)/P_1 = 1 - P_2/P_1$ . The decompression rate shows the value of the pressure drop relative to the adaptation pressure. For our studies, we have used the data for fish older than 12 months old from three families (Percidae sp., Cyprinidae sp., and Salmonidae sp.). We have only used the data from those experiments where decompression from the adaptation pressure ( $P_1$ ) down to the minimum pressure ( $P_2$ ) occurred rapidly (less than in 5 seconds). Such a mode of pressure change is typical for the turbines where the pressure changes rapidly and the pressure change range is very significant. The data indicate that increase of the decompression rate increases the fish fatalities. Closed swim bladder fish and bottom-adapted fish have more fatalities. Salmonidae sp. and Clupeidae sp. do not suffer from decompression that much because they can rapidly adjust the amount of gas in their swim bladders. For example, with the decompression rate of 0.85% no Clupeidae species died, and, with  $D = 0.91$ , only 4% of them died (Turnpenney et al., 1992). Cyprinidae sp. have more fatalities than the

Salmonidae sp. for the same decompression values, but slightly less than the typical representatives of closed swim bladder fish as Percidae sp. Even surface adapted percids experienced 100% fatalities at  $D > 0.8$ .

It can be assumed that the fish losses are significant at  $D > 0.6$ .

It looks like this decompression rate can be defined as critical and it can be used as a criterion for estimation of fish mortalities resulting from decompression immediately downstream from the turbine blades.

Cada et al. (1997) made the same conclusion, while Bell (1990) and ARL (1996) concluded that the critical decompression value for Salmonidae sp. can be 0.7.

Fish injuries and losses, to a large extent, depend on the decompression rate.

The difference in the values given in Fig. 5.15 can be explained by the fact that different species are presented there and also by the various intensities of the pressure change. Specifically, the pressure change ranged from immediate pressure drop to 54 kPa/sec pressure drop. Very few studies have been made on how the decompression rate affects the fish. Most of them simply state that, if the decompression rate goes up, more fish may die. However, since most experiments have been performed under various conditions and by various methods, there is no way they can be summarized. Therefore we have limited ourselves by a small set of data (Fig. 5.16) where the effect of the decompression rate on fish mortalities has been studied explicitly. For example, for roach and moderlieschen adapted for 400 kPa, various rates of pressure drop to 100 kPa (atmospheric pressure) have caused various results (Tsvetkov et al., 1972). 100% of roach 20 – 25 mm fry died at 300 kPa/sec, 56% of them died at 30 kPa/sec and only 10% died at 10 kPa/sec. Moderlieschen of 15 – 25 mm long had much lower fatalities under the same conditions. Young Salmonidae sp. had even lower fatalities. Their mortality rate exceeded 10% only at 70 kPa/sec. Since it takes the fish 15 seconds to pass the turbine, we can estimate how the hydrostatic pressure change affects the fish. For example, for fish adapted for 30 m deep water, at the decompression rate of 30 kPa/sec 15% of moderlieschen and 52% of roach can die, but no Salmonidae sp. losses will occur.

Fish mortality, %

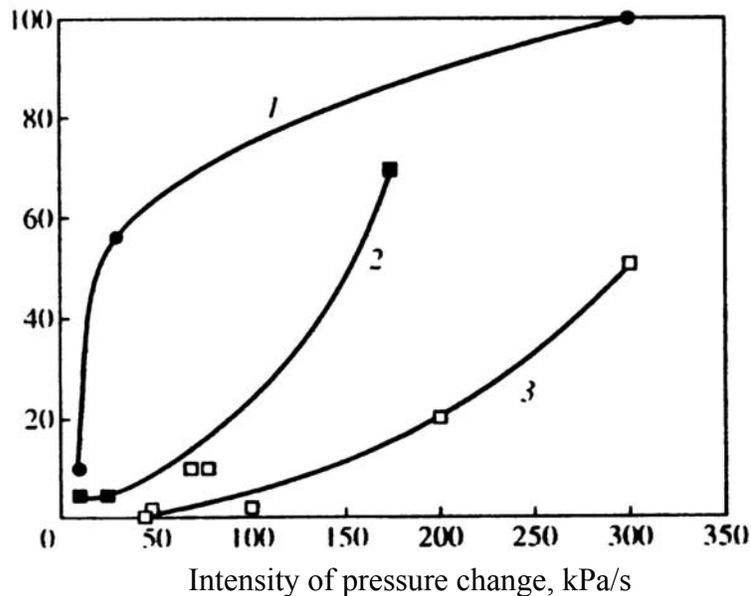


Figure 5.16 Fish losses as a function of pressure change rate (quoted from various literature)

1 – roach (20 – 25 mm long); 2 – moderlieschen (15 – 25 mm long); 3 - Salmonidae sp. (60 – 120 mm long)

Fish injuries and death at HPP also significantly depend on their period of ontogenesis. Surface-dwelling larvae are likely to be less affected by the pressure. Beck et al. (1975) exposed roe and larvae of striped bass (*Morone saxatilis*) to pressure changes in various combinations. They were exposed to subatmospheric pressures (44 kPa), which caused some fatalities. The pressure increase from 14 to 3,317 kPa did not cause any larvae fatalities. Some fatalities were observed with the rapid pressure drop by 86% relative to their adaptation pressure. Cada et al. (1980) obtained similar results for largemouth bass (*Micropterus salmoides*) and channel catfish (*Ictalurus punctatus*) larvae that were exposed to pressure ranges of 56 – 146 kPa. Kedl and Coutant (1976) experimented with bluegill (*Lepomis macrochirus*) larvae, common carp larvae, white bass (*Morone chrysops*) and striped bass (*Morone saxatilis*) larvae, reducing the pressure from 200 to 5 kPa. Ginn et al. (1978) exposed carp larvae to rapid decompression from 100 to 53 kPa. No fish fatalities were observed for any of these conditions.

However, fish losses can still be common for bottom-adapted fish. For example, the roach larvae at C<sub>2</sub> stage adapted to the high pressures experienced 67% fatalities with the 100 kPa pressure change (Tsvetkov et al., 1972). Over 90% of Northern pike and roach larvae died in Fedyaj's experiments (1981) at a rapid pressure drop from 300 – 900 kPa to atmospheric pressure. Jones (1951) stated that late larvae and juvenile species with a well-developed swim bladder taken from over 10 meters deep may die due to rapid decompression.

Thus, pressure change may significantly harm fish during turbine passage. The fish will either receive injuries or die due to rapid decompression. Surface-dwelling fish will be

less harmed by decompression during turbine passage, but bottom-adapted fish will be very severely damaged. As a rule, their swim bladder will be affected. Its walls may rupture because the pressure drop results in a significant increase of the gas volume in the swim bladder. The value of the critical pressure that causes the swim bladder to rupture primarily depends on the fish gas regulation system and the strength of the swim bladder walls. Therefore, the fish fatalities will depend on the genera and age. The number of fatalities will also be different for open versus closed swim bladder fish. The latter suffer more because they are unable to equalize gas pressure in their swim bladder to the external pressure. There will be as much gas in the swim bladder as the adaptation depth is, and, consequently, the fatalities caused by the swim bladder rupture will increase with the increase of the initial (adaptation) pressure and the decompression rate. Another reason for the fatalities will be gas bubble disease, resulting from a rapid decompression. There is no denial of this disease because most injuries at the existing HPPs are associated with gas bubble disease-related hemorrhages. Lynwood (1974) states that from 20 to 40% of salmonidae migrants die of this disease at the HPPs.

To minimize pressure induced-damage, the decompression rate will need to be reduced and its critical values should not be exceeded. Besides, turbine passage of bottom-adapted fish should be avoided.

## 5.4 Cavitation Effect on Fish Injuries and Fatalities at Turbine Passage

Cavitation in turbines occurs when the pressure in the runner blades goes down to the vapor pressure, thereby causing boiling and vaporization of the liquid. The vapor bubbles then travel to the higher pressure zone where they disappear due to condensation (bubble cavitation). Smaller bubbles will be instantaneously filled with fluid, resulting in a local fluid-induced “shock” of up to 10,000 kPa. Cada et al. (1997) consider such fluid-induced “shock” one of the reasons for fish injuries and losses during passage through inefficiently operating turbines.

Apart from the local cavitation bubbles, gas-filled cavitation cavities (caverns) are formed on the blades. These caverns will continuously oscillate and pulse. This type of cavitation is defined as film cavitation. The pressure increase ruptures the cavern, maximizing the shock wave.

The cavitation properties of turbines are characterized by the cavitation coefficient  $\sigma_T$  that is proportional to the ratio of the pressure decrease at the runner blades and the turbine head. The value of this coefficient is estimated experimentally for each series of the turbines. There will be no cavitation if the following condition is met:

$$\sigma_y = \frac{B - H_s - H_p}{H} \sigma_T ,$$

where: B is the local barometric pressure;  $H_s$  is the difference of the water level between the tail race and the location of the runner blades;  $H_p$  is water vapor pressure at a given temperature; and, H is the HPP head.

The equation shows that if the blades are deeply submerged (the negative  $H_s$  increase), the turbine will be cavitation free. However, cavitation-free turbines are very difficult to design, and, therefore, cavitation processes are very common. At some HPPs, cavitation even occurs when the condition  $\sigma_y > \sigma_T$  is met, but, in the latter case, cavitation is local (Bell, 1991).

Cavitation-induced forces and temperature modes result in destruction of some turbine metal components, let alone fish injuries. Cramer, Oligher, 1964, Dadswell et al., 1986 think that fish may overcome pressure change, but not cavitation.

**Table 5-4 Shock Wave-Induced Pressure Resulting in Fresh Water Fish Fatalities for a 25 g Blasting Charge**

Species	Size, mm	Lethal pressure, kPa
Ziege ( <i>Pelecus cultratus</i> )	160 – 250	1,250
Bleak ( <i>Alburnus alburnus</i> )	80 – 120	1,250
Blue bream ( <i>Abramis ballerus</i> )	120 – 200	1,750
Crucian carp ( <i>Carassius carassius</i> )	140 – 180	1,250
European perch ( <i>Perca fluviatilis</i> )	80 – 180	1,750
Pikeperch ( <i>Stizostedion lucioperca</i> )	300 – 360	1,750
Northern pike ( <i>Esox lucius</i> )	300 – 400	1,750
Silver bream ( <i>Blicca bierkna</i> )	140 – 160	2,120
Roach ( <i>Rutilus rutilus</i> )	120 – 200	3,790
Ide ( <i>Leuciscus idus</i> )	150 – 290	3,790
Carp bream ( <i>Abramis brama</i> )	200 – 300	5,980
Tench ( <i>Tinca tinca</i> )	200	13,050

Hubbs, Rechnitzer (1952) were among the first scientists to report on the lethal effect of instantaneous shock wave-related pressure change to marine fishes in conjunction with the study of the effect of underwater explosions on fish. Cavitation shock waves are similar to explosion shock waves. These scientists also found that weak shock waves do not cause fish fatalities.

Other scientists confirmed the effect of shock waves on living organisms (Bogdanov et al., 1958; Tavrizov, 1959; Birznyak, Kuzichkina, 1966; Vyskrebentsev et al., 1968; Rudakovsky et al., 1970; Vekilov, 1973; Balashkand et al., 1980; Kearus, Boyd, 1965; Paterson, Turner, 1968). They have indicated that underwater explosions primarily damage the fish swim bladders, liver and multiple blood vessels, i.e., shock wave-related injuries are very much similar to those induced by pressure changes. The tendencies are

the same, too, i.e., closed swim bladder fish and bottom- and deep-water adapted fish are more inclined to be injured. The shock wave related pressure values resulting in fresh water fish losses are given in Table 5-4.

Table 5-4 shows that the shock wave-related lethal pressure values are close to the cavitation-induced pressure values and, therefore, fish located in the vicinity of the cavitation sources may be injured.

Many authors confirm the lethal effect of cavitation on fish, but very few experiments have been conducted in this field, probably because it is difficult to model the cavitation conditions on a laboratory scale. Muir (1959) was one of the few who was able to develop a lab-scale cavitation model. He exposed 66 mm coho salmon (*Oncorhynchus kisutch*) to the water vaporization pressure environment for a short time and the fish survived it. However, when he exposed it to instantaneous depressurization during 0.4 seconds down to the water vaporization pressure and then back to the atmospheric pressure (it caused generation of the cavitation caverns), over 60% of the tested fish died. Visual examination indicated hemorrhages in their eyes and gills. Muir (1959) concluded that the fish cavitation-related fatalities are caused by a shock, resulting from rupture of the cavitation caverns. In our opinion, the fish fatalities in his experiments may have also resulted from a rapid decompression, which has been discussed in the previous section.

Cramer, Oligher (1964) report on the field-scale cavitation experiments that have demonstrated 52 – 93% of the fish losses in Francis type turbines and 66 – 85% of the fish losses in Kaplan type turbines.

Turnpenny et al. (1992) studied how cavitation affects solid surfaces and found out that its effect is asymmetrical and is directed towards the surface itself. They developed an experimental facility where they were able to model a cavitation bubble and observe how gas bubble condensation affects the fish tissues. In their experiments, they used dead fish and found out that in 33 cases out of 35, the resulting shock wave force is directed towards the fish body. However, they did not detect any injuries in the fish on visual examination. They assumed there were no injuries because their experimental facility was not able to create strong enough shock waves. In the turbine shock waves are much stronger, causing serious injuries.

Postoev (1994) thinks that the cavitation nuclei in the turbine can be various water impurities, including zooplankton. When zooplankton are entrained in the lower pressure zone, gas bubbles form on their surfaces, and those bubbles collapse on compression. Those “microexplosions” destroy or injure the plankton organisms.

It is still difficult to draw any well-defined conclusion on how cavitation affects turbine-passed fish because experimental data are insufficient and there is no explicit proof available that cavitation directly causes fish fatalities. However, many present-day authors have described cavitation as one of the factors affecting turbine-passed fish (Monten, 1985; Davies, 1988; Cada, 1990; Cada et al., 1997). It is obvious that shock waves that may cause damage to the turbine metal components may also kill the fish. But

laboratory-scale experiments show that the cavitation zones may be very limited and most turbine-entrained fish may avoid this zone entirely. Therefore, only few migrants may die of cavitation and no mass fatalities may occur. However, V.S. Postoev (1994) indicates that even zooplankton can form the cavitation nucleus. It seems that larval fish may have the same function, and the closer their size is to that of the cavitation bubble, the stronger the shock wave effect will be because it will affect the greater part of their body. Bubble cavitation, consequently, is not so harmful for adult fish and may only cause minor injuries. Thus, cavitation may have the most damaging effect on larval fish.

To minimize the cavitation effect on turbine-passed fish, it is best to avoid cavitation during turbine operation and depressurization right after the fish pass the turbine. If cavitation cannot be completely avoided, some alternative options have been offered, e.g. flow aeration (Daily, 1986; Hamilton, 1983a, b, 1984; Postoev, 1994). Flow aeration will allow air bubbles to be the cavitation nuclei, thereby removing this role from zooplankton and larval fish.

## 5.5 Turbulence as a Factor of Fish Injuries and Fatalities in HPP Turbine Penstock

Turbulent flows, unlike laminar flows, are characterized by a chaotic movement of fluid particles. There may be multiple various local particle movements in directions that are different from that of the bulk flow. The turbine-entrained fish will not only be exposed to pressure change-induced forces, but also to hydrodynamic forces caused by the turbulent currents. Those hydrodynamic forces may result from changes of the average bulk flow, instantaneous small-scale velocity changes in turbulent eddies, change of direction of the turbulent flows, and collision with solid surfaces. These situations are very common near the turbine penstock walls and along the leading edges of the rotating turbine blades (Monten, 1985). In those areas, various values and directions of the hydrodynamic forces to various parts of the fish body cause typical injuries, such as inverted gills and torn away head (Cramer, Oligher, 1964; Dadswell et al., 1986; Travade et al., 1987).

The lab turbulence-induced fish injures studies can be divided into two groups.

The *first* group includes studies on how the currents affect fish in the vicinity of solid surfaces. The current in the water layer adjacent to the solid surface is slower than the bulk flow current, and the difference in their velocity creates shear stresses. Since the water layer adjacent to the solid surface is not wide, those studies have been performed on roe and larval fish, the size of which is comparable to that of the water layer.

The *second* group of studies evaluates how two flows affect the fish, and these two flows may move in two different directions or in one direction but at various velocities. In those experiments, the flow size is comparable to the adult fish size and the current velocities are pretty high.

The greatest amount of research has been performed for fish passage through tubes of various diameter (Table 5-5).

Kedl and Coutant (1976) sent larvae of seven fresh water fish species through a 2.2 cm tube at 5.8 m/sec current velocity. Less than 5% fatalities were observed.

O'Connor and Poje (1979) exposed striped bass (*Morone saxatilis*) larvae to turbulence in a tube at 3.0 m/sec. In this case, fish mortality was not significant and the authors made the conclusion that turbulence should not be considered the major factor that affects fish mortality.

Cada et al. (1980) used larvae and juvenile fish in their experiments. They changed the pressure from 56 to 146 kPa in a 3.2 cm diameter tube. Such pressure change and turbulence mode significantly affected 7 mm carp larvae. Mortality ranged from 16 to 84%. The mortality of bluegill (*Lepomis macrochirus*), mosquitofish (*Gambusia affinis*), channel catfish (*Ictalurus punctatus*) and largemouth bass (*Micropterus salmoides*) of 12 – 30 mm long did not exceed 2 %.

It is difficult to directly apply these data for evaluation of the turbine conditions because it is difficult to simulate the actual HPP current velocities that may change from 3 to 12 m/sec and more. The experiments were, as a rule, performed at the lower actual velocity value. However, these data provide some information on the general tendencies of the HPP turbulence effect on ichthyoplankton.

The second group of studies simulated more rigid conditions of turbulence. There have been very few studies of this kind, but multiple research and evaluation methods have been applied.

**Table 5-5 Fish mortality following passage through tubes at various current velocities**

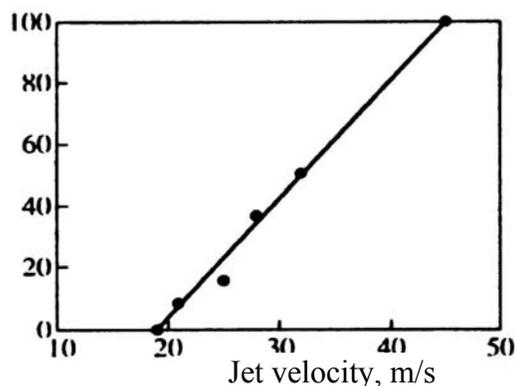
Species	Body length (mm), development stage	Current velocity, m/sec	Mortality, %	Reference
Bluegill ( <i>Lepomis macrochirus</i> )	10 – 12	4.6	Insignificant	Kedl, Coutant, 1976
	25 - 30	4.6	Insignificant	
Striped bass ( <i>Morone saxatilis</i> )	4 - 6	5.8	< 5	
White bass ( <i>Morone chrysops</i> )	6 - 9	5.8	< 5	
Common carp ( <i>Cyprinus carpio</i> )	6 - 10	5.8	< 5	
Mosquitofish ( <i>Gambusia affinis</i> )	6 - 30	5.8	< 5	
Striped bass ( <i>Morone saxatilis</i> )	Prolarvae	3.0	Insignificant	O'Connor, Poje, 1979
	Early larvae	3.0	Insignificant	
	Common carp	7	1.3	
				Cada et al., 1981

Species	Body length (mm), development stage	Current velocity, m/sec	Mortality, %	Reference
( <i>Cyprio carpio</i> )	7	2.4	84	
Mosquitofish	30 - 35	2.4	Insignificant	
( <i>Gambusia affinis</i> )				
Bluegill	18	1.3	Insignificant	
( <i>Lepomis macrochirus</i> )				
Channel catfish				
( <i>Ictalurus punctatus</i> )	16 - 26	2.4	Insignificant	
Largemouth bass				
( <i>Micropterus salmoides</i> )	12	2.4	Insignificant	

Note. Insignificant means that there is no certain difference between the actual mortality and the mortality in the control group.

Bell (1990) studied fish injuries and mortality depending on the velocity of their collision with the water surface. He found that the increase of this velocity increases the fish mortality rate and at  $V = 5$  m/s, the mortality is about 100% (Fig. 5.17). In another publication, Bell (1981) provided the data from the Bonneville Hydraulic Lab on how flow velocity affects fish mortality. The fish were put into the pool to be exposed to a high velocity jet with shear forces occurring on its borders due to the difference in the velocities. The experiments showed that at 3 m/s, small fish mortality exceeded 30%. However, Bell's observations on fish mortality in Foster HPP draft tube at about 5 m/s did not indicate any significant losses of smolts due to heterogeneous current velocities behind the turbine blades.

Mortality, %



Percentage of injured fish, %

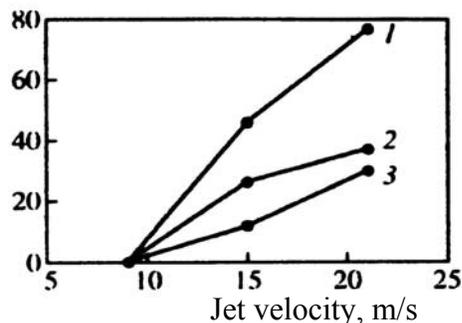


Figure 5.17 (left) Fish mortality as a function of collision with the water surface (Bell, 1990)

Figure 5.18 (right) Percentage of injured juvenile sockeye salmon (*Oncorhynchus nerka*) from contact with a jet of various velocities (ref.: Groves, 1972)

Fish body length: 1: 3 – 6 cm; 2: 6 – 8 cm; 3: 9 – 13 cm

Similar studies have been performed by Groves (1972). He varied the jet velocity from 9 to 36 m/s and contacted the fish with the jet within less than one second. No fish injuries were observed at low jet velocities, but, with increasing velocities, more injuries and fatalities occurred. The fish mostly had injuries in the head (inverted gills and bulging eyes). If the jet velocity of 9 m/sec did not cause any injuries, the velocity of 15 m/sec caused some injuries and, with any further jet velocity increase, the number of injured fish grew. The smaller individuals were injured worse than the larger ones (Fig. 5.18). The worst damage was received if the jet was coming in the direction from the tail toward the head. If the jet affected other body parts or the fish turned its head into the current, hardly any damage was observed. Smaller fish, however, were injured regardless of their orientation in the jet. After the experiments, the fish were held for 48 hours and their mortality was estimated. Not all the injured fishes died (Fig. 5.19.)

Morgan et al. (1976) used rotating cylinders in their experiments, generating shear stresses. They placed the striped bass (*Morone saxatilis*) and white bass (*Morone chrysops*) larvae and roe into the space between the cylinders and exposed them to estimated shear stresses in the range of 0.0076 – 0.040 kPa for 1 – 20 minutes. The experiments showed that the shear stresses of 0.035 kPa had caused 38% mortality of the larvae after one minute exposure, 52% after two minutes exposure and 75% after three minutes exposure. It should be noted that the shear stresses in the turbine may reach over 4 kPa (Cada et al., 1997).

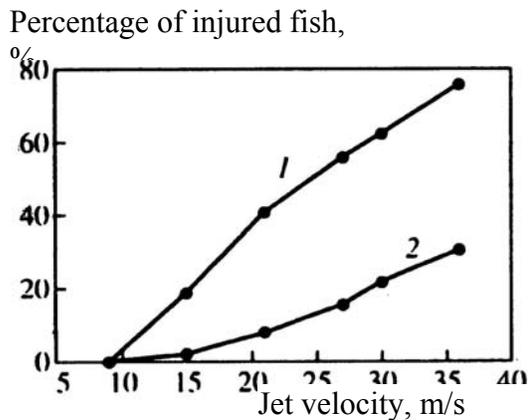


Figure 5.19 Percentage of injured (1) and killed (2) juvenile sockeye salmon (*Oncorhynchus nerka*) (8.5 – 11 cm long) from contact with a jet of various velocities (ref.: Groves, 1972)

Turnpenny et al. (1992) placed various fish species under the jet, going from the nozzle to the water tank. The jet velocity ranged from 5 to 21 m/sec, thereby creating about 3.4 kPa of shear stresses. The fish were exposed to those shear stresses for a long time, and their injuries and mortality were measured afterwards. The experiments on one year old Atlantic salmon (*Salmo salar*), rainbow trout (*Oncorhynchus mykiss*), and sea trout (*Salmo trutta*) that were performed at the jet velocity of 15 m/s, showed that the fish had lost part of their scales, but did not have any other damage and survived. Further increase of the jet velocity caused injuries, resulting in fatalities (Table 5-6). The fish suffered from a loss of mucous membranes and eye damage (retina rupture, bulging eyes, and

hemorrhages). The fish that died seven days after the experiment had severe fungal infections, probably due to a loss of mucous membranes. Twaite shad (*Alosa fallax*) and Atlantic herring (*Clupea harengus*) appeared to be less tolerant to shear stresses, being killed within the first hours even at the minimal jet velocity (5.4 m/sec). They suffered from eye damage and loss, gill inversion and bleeding, as well as a significant loss of scales and mucous membranes. The American eel (*Anguilla rostrata*), however, did not appear to have any visible injuries, apart from a loss of the mucous membrane. They were not killed even by the highest jet velocities (21 m/sec).

T.A. Muravenko and V.V. Trophimov (1981) placed carp bream juveniles through the water jet pump with initial jet velocities of 15, 20 and 25 m/sec. They found that the number of killed fish grew with an increase of the jet velocity and decreased with the increase of the ratio between the nozzle diameter and the mixing chamber diameter (Fig. 5.20). The latter determined the velocity of the flow parallel to the water jet. If the ratio goes up, the speed of the flow grows, thereby reducing the jet velocity. B.S. Malevanchik and I.V. Nikanorova (1984) think that, to preclude any fish fatalities, the difference between the velocities of the two should not exceed 6 – 8 m/sec. Many more experiments on turbulence have been conducted and all of them have shown that turbulence may cause fish injuries, but not all fish suffered from turbulence-related shear stresses equally. Groves (1972) and Turnpenny et al. (1992) have demonstrated that younger fishes suffer from shear stresses more than older fishes, probably because they are less resistant to the jet due to their smaller size and also because most of their body surface contacts the jet. Turnpenny et al. (1992) indicate that their experiments simulated micro-scale turbulence effects of a smaller area of the jet contacting a certain body part of the fish. Beyond those micro-scale effects, the turbine also generates large-scale intensive turbulence, exposing the turbine entrained fish to expansion, compression and spinning. Such effects have not been thoroughly studied yet, but the performed experiments with eggs and larvae give some ideas about what is going on there. These studies show that even small values of large-scale stresses tend to cause mass fatalities of ichthyoplankton (Kedl, Coutant, 1976; O'Connor, Poje, 1979; Cada et al., 1980).

**Table 5-6 Fish injuries and mortality as a function of jet velocity (ref.: Turnpenny et al., 1992)**

Species	Age, years	Jet velocity, m/s	Mortality, %	Injuries, % of the total number of fish		
				Loss of scale	Eyes	Gills
Atlantic Salmon ( <i>Salmon salar</i> )	2	5.4	0	5.7	0	0
		10.4	0	4.4	0	0
		16.4	8	8.0	28	0
		> 20.9	12	4.6	32	0
Rainbow Trout ( <i>Oncorhynchus mykiss</i> )	1	16.4	3.8	0	0	0
		> 20.9	5.0	10	2	

Species	Age, years	Jet velocity, m/s	Mortality, %	Injuries, % of the total number of fish		
				Loss of scale	Eyes	Gills
Sea Trout ( <i>Salmo trutta</i> )	1/2	10.4	0	0	0	0
		16.4	20	5.0	10	0
		> 20.9	10	5.0	10	10
Atlantic herring ( <i>Clupea harengus</i> )	0+	5.4	100	8.2	30	0
		10.4	100	24.0	60	0
		16.4	100	58.0	60	40
		> 20.9	100	90.0	60	20
Twaite Shad ( <i>Alosa fallax</i> )		> 20.9	100	90.0	40	20
American Eel ( <i>Anguilla rostrata</i> )	Not Indicated	5.4	0	These species do not have scales	0	0
		10.4	0		0	0
		16.4	0		0	0
		> 20.9	0		0	0

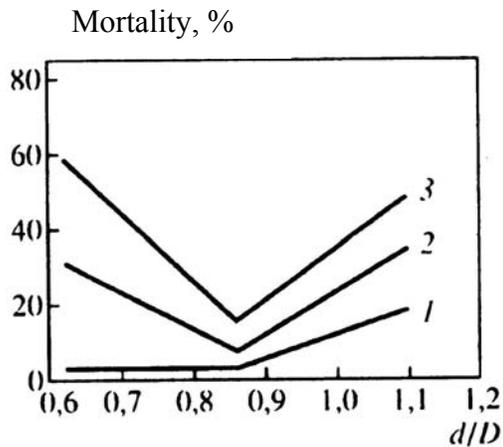


Figure 5-20 Juvenile carp bream mortality (20 – 30 mm long) as a function of nozzle diameter (d) /mixing chamber diameter (D) ratio with the constant jet velocity in the nozzle cross section

1 – 15 m/sec; 2 – 20 m/sec; 3 – 25 m/sec (ref.: Muravenko, Trofimov, 1981)

Thus, the conclusion is that turbulence significantly affects fish injuries and losses, especially juvenile fish injuries and losses resulting from turbine passage. These losses can be minimized by reducing the current velocities in the penstock, thereby reducing the shear stresses and minimizing turbulence.

## 5.6 Fish Injuries Resulting from Contact with Structural Components of the Turbines

While going through the turbine, the fish may collide with turbine structural components, primarily the immobile blades of the stay vanes and wicket gates and the moving blades of the turbine runner. To a large extent, their collision with the runner blades will be more significant.

It is known (Pavlov et al., 1981; Bell, 1990) that if the fish hit a solid surface, it may result in their death, depending on the speed of fish movement towards the barrier. Bell (1990) indicated that such a collision can be fatal at 0.5 m/sec, and at 2.4 m/sec the mortality of small fish may exceed 90 % (Fig. 5.21). Pavlov et al. (1981) dropped European perch (*Perca fluviatilis*) juveniles of 30–40 mm long to a solid surface from 3–11 m heights. The greatest mortality value was observed for the final speed of 7 m/sec. All these experiments show that collision with the operational components of the turbines have severe consequences for the fish. Hematomas, deep cuts, loss of scales and body parts, and spine fractures appear to be the most typical injuries from such collisions.

However, not all the fishes going through the turbines are injured or killed as a result of a collision with the solid surfaces. It primarily depends on the characteristics of the fish and of the turbine design (a number of runner blades, rotation speed and the blade gap size, etc.). It is also important to know where specifically the fish enters the inter-blade space, its orientation and its speed relative to the blade movement.

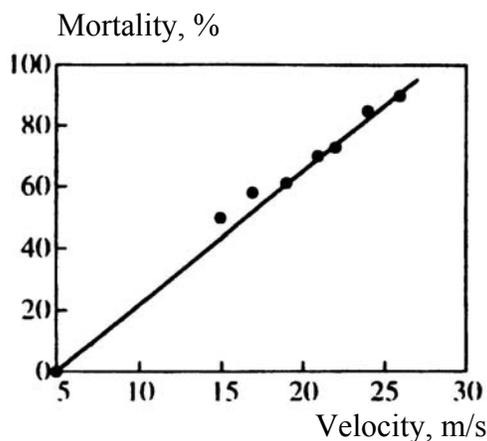


Figure 5.21 Fish mortality as a function of speed of their collision with the solid surface (Bell, 1990)

Monten (1985) thinks that the majority of fish are killed due to their contact with the runner blades. The probability of their collision with the runner blades, as well as the severity of this collision, depend on the fish size, its speed and direction of movement, and well the distance between the runner blades. The relative speed and direction of the fish movement are connected with the flow kinetics and the movements of the runner, specifically, they form an angle for the migrants to enter the inter-blade space and also affect the force of the collision. Monten experimented with eels and Atlantic salmon

smolts at HPPs and confirmed his assumption that most fishes are killed as a result of their collision with the runner blades.

Turnpenny et al. (1992) performed lab-scale experiments, studying collision of fishes with runner blades of various designs and tried to identify how the fish size, orientation and position affect their injuries and mortalities. Their experimental system consisted of a transparent tank where a model of the runner blade was installed. The simulated rotating turbine blade was supplied with a spring to initiate a blow. The rotation speed of that simulated blade was 5 – 7 m/s, which corresponded to the estimated speed of the fish collision with the turbine blade in the vicinity of the turbine shaft (near the tips of the blades, the speed of collision is usually about 20 m/sec). Various blade profiles were used in the experiments to simulate the acute and the obtuse part of the blade.

The obtuse blade collision experiments showed that, at 5.2 m/s, no damage to sea trout (*Salmo trutta*), *Scombrophyraena gigas*, and American eel (*Anguilla rostrata*) had been made. However, their collision with the acute profiles at about 7 m/s caused severe injuries of most species, including but not limited to a loss of scale and mucous membranes, bruises, eye damage, internal bleeding, deep cuts, and spine fracture.

The experiments have shown that the fish mass and the location of their center of gravity relative to the direction of the blade movement affect the probability of the collision. Specifically, as water envelops the blades from the sides, the smaller fish will drift with the flow along the edges of the blades, without contacting them. Larger fishes will move by inertia for some time and they are less likely to go with the flow. Their probability of contacting the blade depends on the balance between the lateral water thrust and the fish's inertia. Individuals below 20 g drifted with the flow and only 13.7% of them contacted the blade. Fish of over 200 g collided with the blade in 75% of all cases.

It seems impossible to estimate exactly how many fish are injured and killed resulting from their collisions with the turbine components due to the complexity of their passage through the turbines. To a large extent, the probability of contact depends on the fish size, mass, flexibility, location in the penstock, orientation, swimming speed and flow velocity, gap size between the blades, blade thickness and speed of the blade movement. Therefore, only some rough estimates have been made, using the equations for calculations of a probability of fish contact with the runner blades.

Hinterleitner (ref.: Tikhij, Victorov, 1940) was the first to develop an equation to calculate potential collision of the fish with the runner blades in 1937. His equation permitted an estimation of the fish safe body length ( $l_b$ ) that will pass the turbine without damage:

$$l_b = 1.5S \cdot V \cdot v^{-1},$$

where: S is the distance between the blades, V is the flow velocity at the input to the inter-blade space of the turbine runner; v is the circumferential velocity.

To obtain the estimated relationship, let us consider the fish movement in the inter-blade space of the Kaplan type turbine (Fig. 5.22). If the fish is located at the surface of the upper edge of the preceding blade, then, to avoid its contact with the next blade in line, it needs to move vertically for the distance that will equal its body length within the time the blade moves horizontally from point 1 to point 2.

The time ( $t$ ), during which the fish goes the distance that equals its body length ( $l$ ) is as follows:

$$t_p = l/v, \quad (5.1)$$

where:  $v$  is the flow velocity.

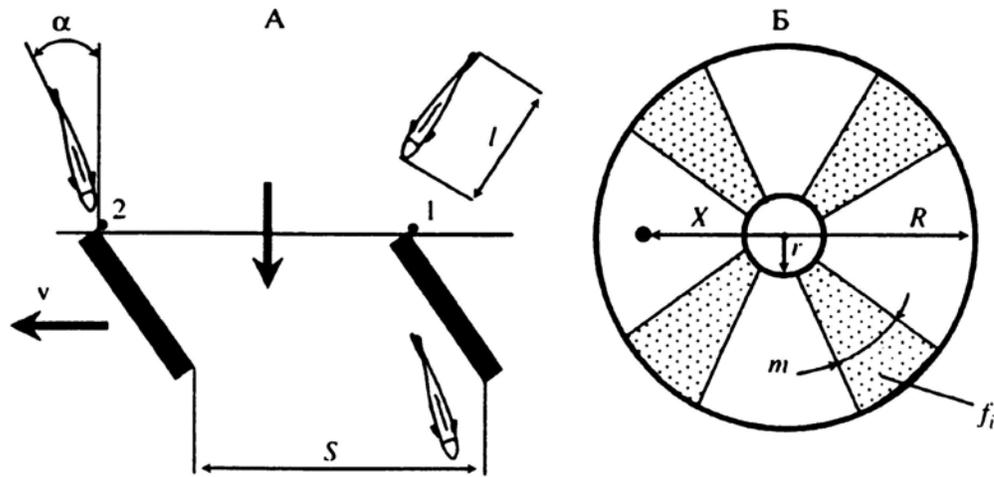


Figure 5.22 The schematic of the fish collision with the Kaplan type turbine runner blade.

A – in the cross section; B – in the plan view.

The time for the runner blade movement can be estimated as follows:

$$t_\pi = S/v, \quad (5.2)$$

where:  $S$  is the distance between the blade edges, and  $v$  is the circumferential velocity.

Converting the equation  $t_p = t_\pi$ , we'll obtain the following:

$$l = S \cdot v^{-1}. \quad (5.3)$$

Taking into account the fact that  $S = 2\pi \cdot X/N$ ,  $v = w \cdot X$ ,

$$\text{And } n = 2\pi V \cdot (w \cdot N)^{-1} = V \cdot (n \cdot N)^{-1}, \quad (5.4)$$

where:  $X$  is the radial distance from the center of the turbine to the fish location;  $w$  the angular velocity;  $N$  is a number of the runner blades, and  $n$  is the rotation of the runner, in revolutions per second.

Equation 5.4 provides a relationship between fish size and flow velocity, as well as the turbine parameters. It allows us to determine the minimal fish size to assure contact with the turbine runner blades. The smaller the fish is, the less probable the contact will be. To estimate the probability, the distance ( $S$ ) from the blade edge to the fish location should be expressed as follows:

$$S = l \cdot v \cdot V^{-1} = l \cdot w \cdot X \cdot V^{-1},$$

or:

$$S = l \cdot 2\pi \cdot n \cdot X \cdot V^{-1}. \quad (5.5)$$

It is obvious that the sector identified by this distance is the field for the fish contact with the runner blades, i.e., the fish that enter that inter-blade space are bound to collide with blade edge. The area of those sectors in the runner surface will be as follows:

$$f = 0.5\pi \cdot (R^2 - r^2) \cdot N \cdot m / 360, \quad (5.6)$$

where:  $m$  is the degree measure of the sector;  $R$  is the runner radius; and  $r$  is the turbine shaft radius.

Taking into account that:

$$m / 360 = S(2 \cdot \pi \cdot R)^{-1} = l \cdot n \cdot V^{-1},$$

we obtain the following:

$$f = 0.5\pi \cdot (R^2 - r^2) \cdot N \cdot l \cdot n \cdot V^{-1}. \quad (5.7)$$

If we assume the fish homogenous approach to the turbine, the ratio of this area to the area of the flow-through part of the runner will identify the probability of the fish collision with the runner blades:

$$P = f / F = N \cdot l \cdot n \cdot V^{-1}. \quad (5.8)$$

Similar dependencies for Francis type turbines have been obtained by von Raben (1957). Using that dependency, Dadswell et al. (1986) found that the probability of the fish collision for the propeller type turbines was very similar to that calculated by von Raben (1957). However, Ruggles and Collins (1981) discovered that the estimated value of the collision was significantly lower than the actual collision probability. They indicated that this discrepancy could be explained by not taking into account the gap between the blades of the wicket gate and the rotating blades of the runner, i.e., the design specifics of that

type of turbines. However, the fish contact the edge of the Francis type turbine, where the circumferential velocity is the greatest, thereby affecting the fish most severely.

The von Raben calculations show that the probability of smaller fish contacting the runner blades is fairly low. For example, Cada (1990) estimated that for a bulb turbine, probability of blade contact is only 0.1% for fish eggs, or it can even be lower with a lower flow velocity. The probability does not exceed 2% for most of the fish larvae, and, for juvenile fish of 40 mm, this probability is about 5%. Such collision appears to be the most probable for the larger fish. Therefore, adult fishes are more exposed to the mechanical impact of the turbine than the young fishes.

Even a small probability of the young fish collision with the runner blades can be overestimated because the contact with the blades does not necessarily cause fish losses. For example, the fish may enter the inter-blade space at an angle, not necessarily perpendicular to the rotation surface. The smaller this angle is, the faster the fish will pass the blades, without contacting them. The severity of the collision may also vary. The collision will be more severe far from the center of the turbine due to a high circumferential velocity. Beyond that, a head-on collision will be more damaging than any “sliding” collision. It is also important to take into consideration the flexibility of fishes, that will vary from species to species, affecting the fish mortality resulting from collision with the turbine components. For example, Monten’s (1985) experiments at Montala dam showed that the mortality of 12-cm long European perch (*Perca fluviatilis*) was 35% higher than that of the salmon\* of the same size. Therefore, the impact may vary, but von Raben’s equation (1957) does not take these variations into account. To adjust that equation, the error coefficient of 0.43 has been added (Dadswell et al., 1986). Obviously, the error coefficient is supposed to vary, depending on the turbine type and the existing hydraulic conditions.

In our opinion, equation (5.8) can be applied for the fishes that are oriented perpendicular to the turbine blade. If they enter the inter-blade space at an angle  $\alpha$ , the equation should be modified as follows:

$$P = l \cdot n \cdot N \cdot \cos(\alpha) \cdot V^{-1}. \quad (5.9)$$

It should be noted that, at  $\alpha = 60^\circ$ ,  $\cos(\alpha) = 0.5$ , which is close to the error coefficient value.

In 1998, at Verkhne-Tulomskaya HPP, we put Sterry sturgeon (*Acipenser stellatus*) smolts into special plastic cases to be retrieved in the tail race. As the experiments showed, 35 out of 50 cases, or 70%, appeared to have collided with the runner blades. Those data have made it possible to compare the predictions of equations (5.9) and (5.10) with the actual data. Specifically, with the case length of 28 cm, a number of blades  $N = 8$ , rotation  $n = 3.1$  revolutions per second, flow rate  $Q = 135 \text{ m}^3/\text{second}$ , the runner diameter  $D = 4.2 \text{ m}$  and  $\alpha = 90^\circ$ , the calculations by (5.9) gives the following collision probability value  $P = 70.9\%$ . It closely matches the actual percentage of the damaged plastic cases, which indicates that (5.9) can be used for the actual collision calculations.

Monten has proposed another equation for the runner blade collision probability calculations:

$$P = 0.5l/s, \quad (5.10)$$

where:  $s$  is the relative opening of the runner blades defined as the shortest distance between the edge of the preceding blade and the surface of the following blade.

Monten's studies have demonstrated a good compatibility between the estimated and actual data. Specifically, for the downstream migration of American eels (*Anguilla rostrata*) of 73.5 cm long and the relative opening of the blades of 69 cm, the actual fish losses appeared to be 49%, while the estimated runner blade collision probability was  $P = 53\%$ . At Engabeke HPP, the actual losses of American eels of the same size and  $s = 88.5$  cm were 38.5% with the probability  $P = 41.5\%$ . At the same HPP, the discrepancy between the actual data exceeded the experimental data by 10 – 12% for juvenile Atlantic salmon (*Salmo salar*) of 14.5 cm long (Monten, 1985).

Bell (1991), taking into account the flow kinetics and the motion of the turbine blades, proposed his own equation for estimating the probability of the fish collision with the blades:

$$P = \frac{n}{60} \frac{N \cdot l \cdot \sin(\beta)}{V_r},$$

where:  $N$  is a number of the runner blades;  $n$  is the turbine rotation rate, rpm;  $V_r$  is the radial velocity for Francis type turbines and axial velocity for Kaplan type turbines;  $\beta$  is the angle between the absolute and the tangential velocities for Francis type turbines and between the directions of the axial and absolute velocities for Kaplan type turbines.

The probabilities calculated by this equation appear to be lower than the actual collision data and, in our opinion, this equation can only be used for turbines operating at maximum operational efficiency.

Monten (1985) performed experiments at Motala HPP with the identical load and various turbine rotation velocities (Fig. 5.23). The results obtained on the fish fatalities for various types of turbines and various fish species of identical sizes have shown that an increase of the turbine rotation velocity increases the fish mortality. He has explained it by the fact that the reduction of the turbine rotation velocity reduces the relative velocity of the fish movement, and, at a lower velocity, the fish are not injured while colliding with the runner. Beyond that, he has shown that the clearance between the wicket gate blades and the runner blades in Francis type turbines plays a very important role in helping the fish avoid the contact with the turbine components. The wider the clearance is, the easier it is for the fish to avoid the collision, thereby decreasing their mortality and vice versa. For example, the decrease of this clearance from 6.9 cm down to 2.7 cm increased the mortality of the salmon\* smolts by 18%.

Mortality, %

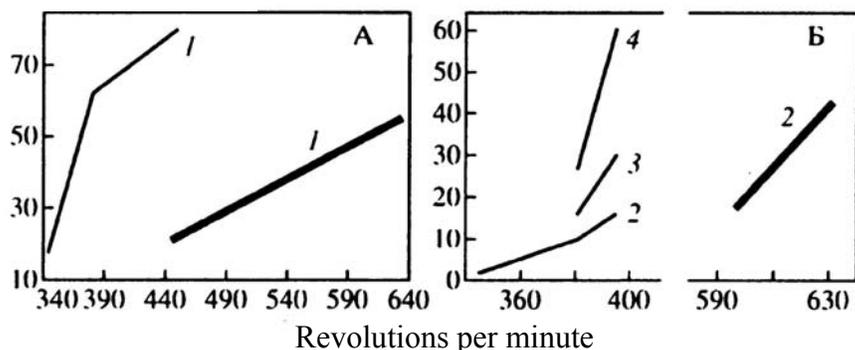


Figure 5.23 European perch (*Perca fluviatilis*) (A) and salmon\* (B) mortality as a function of the number of runner blades in Francis turbine (thinner line) and Kaplan turbine (bold line) (ref.: Monten, 1985)

Fish size: 1: 116 – 130 mm, 2: 41 – 57 mm, 3: 79 – 85 mm, 4: 134 – 137 mm

Thus, collision with the turbine operational components is likely to cause fatalities of large fish, but it appears to be not as harmful for smaller fish, for example, for juvenile fish. Apart from fish size and their distribution in the turbine penstock, the probability of fish collision with the runner blades depends on the water flow and turbine kinetics, as well as the turbine design characteristics, i.e., the number of runner blades, size of clearance between the runner blades or between the wicket gate blades and runner blades. To minimize the probability of fish collision with the turbine components, all these parameters need to be taken into consideration.

## 5.7 Comparison of the Effects of Various Factors to Fish Injuries and Losses During Their Downstream Migration

This section describes various factors, i.e., HPP head, turbine type, and turbine operational mode, which affect fish injuries and losses resulting from passage through HPP. Special focus has been made on how the type of turbine affects fish mortality because this issue has been discussed in many foreign publications, but no unified solution has been given.

### Evaluation of Combined Effect of Various Factors

During passage through the HPP turbine, all the above mentioned factors affect the fish simultaneously, and, in most cases, it is extremely difficult to figure out which factor has caused which damage. It should be taken into account that their total effect, as well as the associated factors, such as water temperature, oxygen and nitrogen content in water, as well as presence of toxic materials in water, etc., may aggravate or mitigate the potential fish injuries. The associated factors affect the fish physiological state both prior to turbine entrainment and after the turbine passage. Therefore, under some conditions, even badly

injured fish may survive, and, under other conditions, even lightly injured fish may die (Cada et al., 1980; Barton et al., 1968; Mesa, 1994; Cada et al., 1997).

Various factors may cause similar injuries (Table 5-7).

At Big Cliff HPP (head of 21 – 27 m), Bell (1981) studied how various factors affected the fish injuries and losses (Table 5-8). He concluded that the most severe injuries result from pressure changes rather than the collisions with the turbine components. Other factors, in his opinion, did not cause significant fish losses.

**Table 5-7 Fish injuries resulting from various factors under experimental conditions (ref.: Turnpenny et al., 1992)**

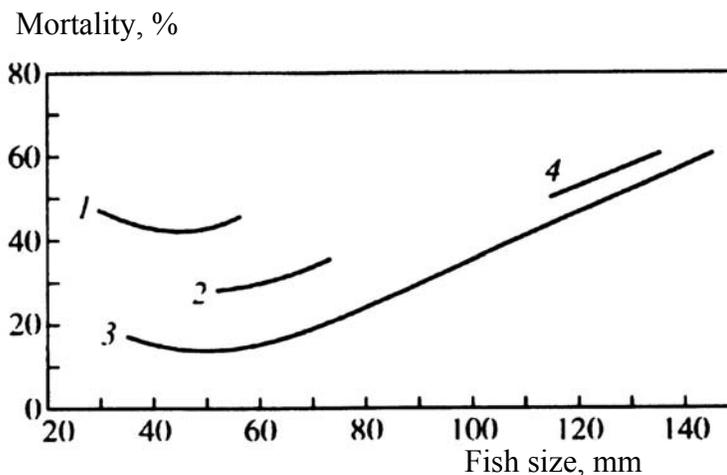
Injury	Pressure change	Shear stresses	Collision with runner blades
Swim bladder rupture	Yes	No	No
Hemorrhages in eyes	Yes	Yes	No
Eye damage	No	Yes	Yes
Loss of scales	No	Yes	Yes
Internal bleeding	No	Yes	Yes
Loss of eggs	Yes	No	No
Gill damage	No	Yes	No

**Table 5-8 Various factors affecting losses of smolts at Big Cliff HPP (ref.: Bell, 1981)**

Causes for fish losses	Fish killed	
	Number of individuals	%
Pressure change	536	53.7
Collision with runner blades	376	37.7
Unknown reasons	86	8.6

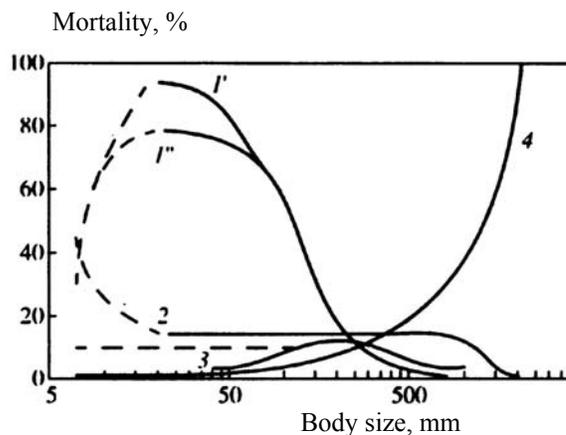
However, there is another opinion. In particular, Monten (1985), having studied fish losses at a number of HPPs, concluded that the fish fatalities had mostly been caused by their collision with the runner blades. The turbines are virtually impassable for large fish. Almost all of them die from their collision with the runner blades. For example, at Lengor HPP, the mortality of eels\* of 73.5 cm long was 93.8%, of 56.5 cm long, the mortality was 77.9%, and for salmon\* smolts of 14.5 cm long, the mortality was only 16.2% (Monten, 1985).

The difference in the authors' opinions on the most harmful factor causing fish losses indicates that these factors need to be taken into account together with the entire range of morphological and physiological characteristics of fishes. The degree and type of injuries will, to a large extent, depend on a specific kind of fish species, its size and age. In this respect, we need to take into account such characteristics as scale density, skin thickness, flexibility, and shape. Monten (1985) experimentally proved that the consequences of fish collision with the runner blades will depend on fish size and the fish species (Fig. 5.24). Cavitation and turbulence appear to be the most hazardous for larval fish. Larger fish are more severely affected by pressure changes and collisions with the runner blades, and the larger the fish, the more likely is the probability of such collision. Closed swim bladder fishes are more sensitive to pressure changes than open swim bladder fishes.



**Figure 5.24 Mortality of various fish species resulting from collision with runner blades of Kaplan turbines as a function of the fish size (Monten, 1985)**

1 – Ide (*Leuciscus ide*); 2 – Minnow (*Phoxinus phoxinus*); 3 – Salmon\*; 4 – European perch (*Perca fluviatilis*)



**Figure 5.25 Fish mortality as a function of their size affected by various factors**

1' and 1'' – pressure for bottom adapted and surface dwelling fish, respectively; 2 – cavitation; 3 – turbulence; 4 – collision with turbine components

Dadswell and Rulifson (1994) hypothetically estimated the degree of effect of various factors to turbine entrainment associated losses (Fig. 5.25). According to their data, the runner blades' collision-induced mortality increases with the fish size. The situation with the pressure-induced injuries is that the larger the fish, the less damaging the pressure change. In their opinion, on the average, the least hazardous factor seems to be associated with shear stresses. Only fish below 20 cm are not resistant to this factor. They state that the percentage of cavitation-induced fish losses remains constant for fish up to 100 cm long, and then it goes down. Many of those statements have been experimentally proved, but, nevertheless, a few of them need adjustments and additional studies, especially pressure changes, cavitation and turbulence. In our opinion, the effect of the pressure change on larval fish has been unjustifiably overestimated, while the effect of cavitation and turbulence, on the contrary, has been underestimated. Therefore, we have made some adjustments in Fig. 5.25. All the adjustments are shown in dotted lines.

#### Effect of HPP Head

All factors that affect the fish during passage through HPP turbines mainly depend on the design (type) of the turbine and the HPP head. The latter determines the pressure change, shear stresses and cavitation. If the head increases, the pressure changes more drastically and the current velocity goes up, thereby aggravating the hydraulic conditions in the HPP penstock. Thus, the fish mortality goes up with the HPP head increase (Fig. 5.26).

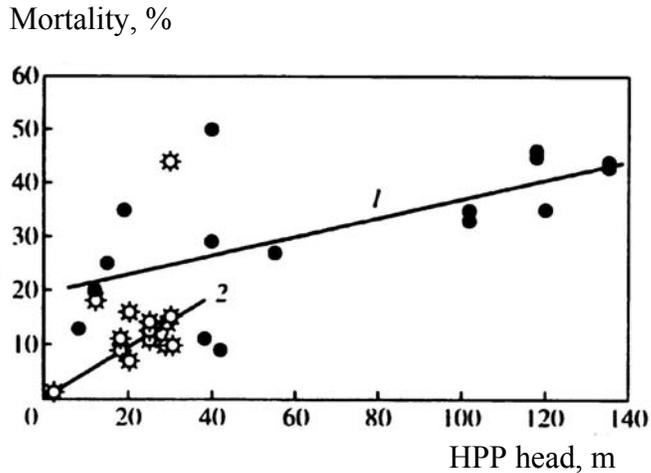


Figure 5.26 Mortality of Salmonidae species as a function of HPP head value for Francis turbines (1) and Kaplan (2) turbines (quoted from various sources)

**Table 5-9 Percentage of various injuries and mortality at HPPs with various head values and various depths of water intake**

Parameter	Ivan'kovskaya HPP	Ust'-Khantajskaya HPP	Kapchagajskaya HPP	Mostiste	Al. Stambolijski
HPP head, m	11	54	35	30	40
Head race depth, m	14	31	26	29	30
Injured, %	7.1	78.0	88.9	75	100
Mortality, %	Not estimated		71.0	65	100

Note. Percentage of Percidae *sp.* of 50 – 150 mm long (European perch (*Perca fluviatilis*), pikeperch (*Stizostedion lucioperca*), and ruffe (*Gymnocephalus cernuus*) with various injuries and their mortality at HPPs with various head values and various depth of water intake (percentage from the total amount of the examined fish)

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Comparison of the data on injuries and mortality of Percidae species of similar sizes at various HPPs (Table 5-9) shows that fish mortality will be higher with the larger HPP head values and deeper head race. In this case, these are Al.Stambolijski, Mostiste and Kapchagajskaya HPPs. These two parameters primarily affect how the pressure change affects the fish. For example, the water intake depth determines the pressure that affects the fish entering the HPP penstock.

#### **Effect of Turbine Type**

The type of turbine affects turbulence and the probability of collision with the turbine blades. At Motala HPP, Monten (1985) compared two types of turbines, i.e., Francis and Kaplan turbines, applying identical loads to them. He found that Kaplan-type turbines cause slightly more fish losses than Francis-type turbines, but this difference is fairly insignificant, and, specifically, for the salmon\* smolts, it has not exceeded 5%. 36% of fishes experienced body rupture at Kaplan turbines versus 6% of fishes with similar injuries at Francis type turbines. Monten explained this difference by a harder collision with Kaplan turbine runner blades, in comparison with Francis turbine runner blades. The Kaplan turbine rotation rate is higher by a factor of 1.6 than that of the Francis turbine. A higher rotation rate means a greater number of rotations and, consequently, a greater circumferential speed of the runner blades, causing a stronger collision with the blades. Therefore, we think that there is some inaccuracy in Monten's results.

The most challenging area for fish passage through Francis-type turbines is the clearance between the wicket gate blades and runner blades. It is there that the fish is the most exposed to collisions with the runner blades and turbulent shear stresses. The fish losses in that area depend on the ratio between fish size and the size of the clearance. Beyond that, the fish collision with the runner blades of Francis-type turbines occurs at the

moment of the maximum circumferential velocity of their rotation, thereby aggravating the consequences of this collision.

The wicket gate blades of Kaplan and propeller-type turbines are located higher than the runner blades, thereby reducing mechanical impact of the collision. The maximum impact should be expected on the periphery of the runners, but not near the turbine shaft. Therefore, the severity of injuries depends on where specifically the fish has passed the turbine, and the closer it is to the shaft, the lower is the risk of injuries.

Horizontal bulb turbines, as a rule, do not have a penstock or a spiral chamber. They have a wicket gate that is located away from the runner blades, and the clearances between the runner blades are pretty large. All these parameters, in our opinion, minimize fish losses associated with fish downstream migration through that particular type of turbine.

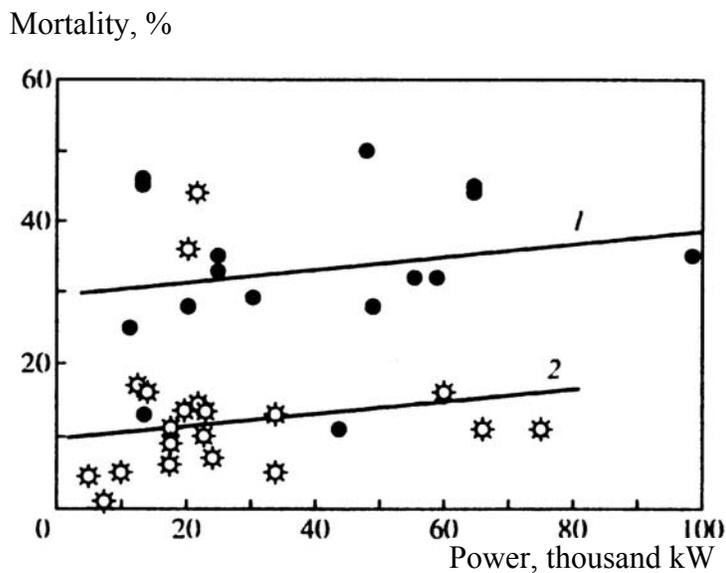


Figure 5.27 Salmonidae species mortality as a function of turbine output for Francis (1) and Kaplan (2) turbines

Nevertheless, the direct angle of the flow entry in Kaplan turbines, in comparison with the tangential angle of Francis turbines, as well as their maximum rotation velocity, may cause more severe collisions with the runner blades. It seems that the fish losses at various types of turbines will depend on specific conditions of their turbine entrainment and passage.

**Table 5-10 Fish mortality at various HPPs with Francis turbines**

HPP	Head, m	Fish species and age (size)	Mortality, %	Reference
Lequille, Nova Scotia	Not indicated	Atlantic salmon ( <i>Salmo salar</i> ), smolts <i>Salmo</i> sp.	40 – 50 15 - 76	Ruggles, Collins, 1981 Collins, Ruggles, 1982
Luddington, Lake Michigan, USA	Not indicated	<i>Oncorhynchus</i> sp., <i>Salmo</i> sp.	45 - 57	Liston, 1979
Raskin HPP, Steve River, Canada	38.0	Sockeye salmon ( <i>Oncorhynchus nerka</i> ), one year old	11	Hamilton, Andrew, 1954
Puntledge River, Canada	102.0	Rainbow trout ( <i>Oncorhynchus mykiss</i> ), juveniles Atlantic salmon ( <i>Salmo salar</i> ), fry	28 – 42 33	Canada Dept. of Fisheries, 1958
Seton Creek, Canada	42.0	Sockeye salmon ( <i>Oncorhynchus nerka</i> ), one year old	9	Andrew, Geen, 1958
Mutala, Sweden	15.0	Atlantic salmon ( <i>Salmo salar</i> ), smolts	25	Monten, 1985
North Fork, Klakamas River USA	40.0	Coho salmon ( <i>Oncorhynchus kisutch</i> )	26 - 32	Gunsolus, Eicher, 1970
Willamette Falls, Willamette River, USA	Not indicated	Steelhead ( <i>Salmo gairdneri</i> ) Chinook salmon ( <i>Oncorhynchus tshawytscha</i> )	13 14	Massey, 1967
West Linn, Willamette River, USA	12.0	rainbow trout ( <i>Oncorhynchus mykiss</i> ) and Chinook salmon ( <i>Oncorhynchus tshawytscha</i> )	20 - 100	Massey, 1967
Cushman HPP-2, Skykomish River, USA	135.0	<i>Oncorhynchus</i> sp. <i>Salmo</i> sp.	23 – 66 16.3 – 70.4	Cramer, Oligher, 1963 ref.: Bell, 1981
Shasta Plant, Sacramento River, USA	100.0 – 146.0	<i>Oncorhynchus</i> and <i>Salmo</i> sp.	10 - 60	Cramer, Oligher, 1964
Lower Elwha, Elwha River, USA	Not indicated	<i>Oncorhynchus</i> sp., fry  Coho salmon ( <i>Oncorhynchus kisutch</i> )	0 37 12 – 28	Schoeneman, Junge, 1954 Wunderlich, 1983 Wunderlich, Dilley, 1985
Glines Canyon, Elwha River, USA	Not indicated	Coho salmon ( <i>Oncorhynchus kisutch</i> ), fry Chinook salmon ( <i>O. tshawytscha</i> ), fry	38 33 30	Schoeneman, Junge, 1954.
Clooney, Scotland	55.0	<i>Salmo</i> sp.	21 - 34	Munro, Campbell, 1961
Kashlia, Scotland	Not indicated	<i>Salmo</i> sp., one year old	53 - 84	Munro, 1966

HPP	Head, m	Fish species and age (size)	Mortality, %	Reference
Volkhovskaya, Volkhov River, Russia	11.5 – 13.0	carp bream ( <i>Abramis brama</i> ) (35 – 37 cm) ide ( <i>Leuciscus idus</i> ) (22 – 27 cm) pikeperch ( <i>Stizostedion lucioperca</i> ) (28 – 37 cm)	12 - 30	
Cazadero, Klackamas River, USA	40.0	Coho salmon ( <i>Oncorhynchus kisutch</i> ) (7 – 8 cm)	50	Ref.: Tikhij, Victorov, 1940
Tange, Guden-Aa River, Denmark	7.0 – 9.0	Rainbow trout ( <i>Oncorhynchus mykiss</i> ) (10 – 22 cm)	13	
Westbirk, Guden-Aa river, Denmark	9.0	Rainbow trout ( <i>Oncorhynchus mykiss</i> ) (10 – 20 cm)	35	
Becker Dam, USA	75.0	Sockeye salmon ( <i>Oncorhynchus nerka</i> ) Coho salmon ( <i>Oncorhynchus kisutch</i> )	66.4 28.3	Munro, Campbell, 1961
Becker Dam, USA	75.0	Sockeye salmon ( <i>Oncorhynchus nerka</i> )	33.6	
Gold Bay, USA	6.0	Sockeye salmon ( <i>Oncorhynchus nerka</i> )	0 – 16.7	
Staton, USA	4.8	Sockeye salmon ( <i>Oncorhynchus nerka</i> )	2.1 – 17	
Leeburg, USA	26.6	Sockeye salmon ( <i>Oncorhynchus nerka</i> )	3.6 – 6	
Lower Elwha, USA	31.2	Species not specified	5	Ref.: Bell, 1981
Seton Creek, USA	42.6		9.2	
Raskin, USA	39.0		10.5	
Crown Zelegrvakh, USA	12.4		18.8 – 29.4	

**Table 5-11 Fish mortality at various HPPs with propeller-type and Kaplan turbines**

HPP	Head, m	Fish species and age (size)	Mortality, %	Reference
Nekkarzimmeri, Germany	Not indicated	Common eels ( <i>Anguilla anguilla</i> ), adult fishes Atlantic salmon ( <i>Salmo salar</i> )	25 – 50 5	Berg, 1986
		American shad ( <i>Alosa sapidissima</i> )	0 - 5	Kynard et al., 1982
Hadley Falls, Connecticut River, USA	18.0	Atlantic herring ( <i>Clupea harengus</i> ) Atlantic salmon ( <i>Salmo salar</i> ) American shad ( <i>Alosa sapidissima</i> )	63 – 83 13 0 – 17	Stier, 1983 Kynard et al., 1982 Bell, 1982
Holyoke, Connecticut River, USA	25.0	American shad ( <i>Alosa sapidissima</i> ) Atlantic salmon ( <i>Salmo salar</i> )	21 12 - 14	Bell, Kynard, 1985 Stier, Kynard, 1986
McNary, Columbia River, USA	25.0	<i>Oncorhynchus</i> sp. juveniles	9 - 13	Bentley, Raymond, 1960
Bonneville, Columbia River, USA	18.0	<i>Oncorhynchus</i> sp.	11	Schoeneman et al., 1961
Ice Harbor, Columbia River, USA	27 - 34	Coho salmon ( <i>Oncorhynchus kisutch</i> )	10 – 19	Long et al., 1968
Wells, Columbia River, USA	16 – 24	Rainbow trout ( <i>Oncorhynchus mykiss</i> )	16	Weitkamp et al., 1985
Big Cliff, North Santiam River, USA	25.0	Chinook salmon ( <i>Oncorhynchus tshawytscha</i> ) Chinook salmon ( <i>Oncorhynchus tshawytscha</i> )	5 - 22	Oligher, Donaldson, 1965
Foster, South Santiam River, USA	30.0	Chinook salmon ( <i>Oncorhynchus tshawytscha</i> ) Chinook salmon ( <i>Oncorhynchus tshawytscha</i> ) <i>Oncorhynchus</i> sp.	6 11 9	Wagner, Ingram, 1973 Bell, Bruya, 1981 Schoeneman et al., 1961
Sullivan, Willamette River, USA	12.4	Rainbow trout ( <i>Oncorhynchus mykiss</i> ) Chinook salmon ( <i>Oncorhynchus tshawytscha</i> )	8 – 26 14 - 26	Massey, 1967

HPP	Head, m	Fish species and age (size)	Mortality, %	Reference
Big Cliff, North Santiam River, USA	29.0	Chinook salmon ( <i>Oncorhynchus tshawytscha</i> )	5 – 22	Oligher, Donaldson, 1965
		Chinook salmon ( <i>Oncorhynchus tshawytscha</i> ) (15 cm)	5.2 – 12.7	Ref.: Bell, 1981
		Rainbow trout ( <i>Oncorhynchus mykiss</i> ) (18 cm)	3.0 – 17.5	
Invergarry, Scotland	30.0	<i>Salmo</i> sp. <i>Salmo</i> sp., fry	16 7 - 13	Munro, 1965 Munro, 1964
Helgion, Sweden		Juvenile (various species)	50	
Lilla-Adet, HPP, Gota River, Sweden	6 – 7	Juvenile (various species)	4	
Silkeborg, Guden-Aa River, Denmark	2	Rainbow trout ( <i>Oncorhynchus mykiss</i> ) (10 – 20 cm)	1	Ref.: Tikhij, Victorov, 1940
Svirskaya, Svir River, Russia	10 - 11	Carp bream ( <i>Abramis brama</i> ), ide ( <i>Leuciscus idus</i> ), Northern pike ( <i>Esox lucius</i> ), burbot ( <i>Lota lota</i> ), pikeperch ( <i>Stizostedion lucioperca</i> ), adult fishes	0	
Tusket Falls, USA	6.0	Species not specified	19.0	Ref.: Bell, 1981
Tobique Narrows, USA	22.5		18.3	
Waterville, USA	18.0		4.5 12.7	
McNary, USA	24.0		3.8 – 13.0	
Rocky Reach Dam, USA	25.4	Chinook salmon ( <i>Oncorhynchus tshawytscha</i> )	5.3 – 7.0	Ref.: Mathur et al., 1996

**Table 5-12 Fish mortality at various HPPs with turbines of bulb, Straflo and Ossberger types**

HPP	Head, m	Fish species and age (size)	Mortality, %	Reference
Annapolis, Fundy	5 - 8	American shad ( <i>Alosa sapidissima</i> ), adult fishes	22 – 46	Dadswell et al., 1986
		<i>Alosa</i> sp., young fishes	24	
Essex, Merrimack River	Not indicated	Atlantic salmon ( <i>Salmo salar</i> )	2	Knight, Kuzmeskus, 1982
Rock Island, Columbia River, USA	10 - 14	Coho salmon ( <i>Oncorhynchus kisutch</i> )	7	Olson, Kaczynski, 1980
		Rainbow trout ( <i>Oncorhynchus mykiss</i> )	3	
		Coho salmon ( <i>Oncorhynchus kisutch</i> ) (12 – 15 cm)	4.4 – 9.6	Ref.: Bell, 1981
		Rainbow trout ( <i>Oncorhynchus mykiss</i> ) (16 – 18 cm)	3.1	
Colliersville, Susquehanna River, USA	Not indicated	American shad ( <i>Alosa sapidissima</i> )	50	Gloss et al., 1982
		Striped bass ( <i>Morone saxatilis</i> )	54	
		Atlantic salmon ( <i>Salmo salar</i> )	24 - 62	

A review of the published data (Tables 5.10, 5.11, and 5.12) shows that there are certain well-defined differences in Salmonidae species mortality for various turbine types. Specifically, for Francis turbines, the Salmonidae mortality averaged 31.6%, for Kaplan turbines it is 14.5%, and for bulb turbines, it is 10.7%. However, it should be taken into account that these turbines operate at various heads, thereby making this comparison not quite reliable. Therefore, we have also evaluated all existing data on the smolt mortality from passage through Kaplan or Francis turbines as a function of the turbine output (Fig. 5.27). The result indicate that Francis turbines cause more fish losses than Kaplan turbines.

#### **Effect of the Turbine Operation Mode**

As the studies show, not only the turbine type, but also the operational mode of the turbine, affects the fish mortality. The operational mode of the turbine is related to the degree of opening of the wicket gate. The more open it is, the greater the clearance is between the gates, thereby minimizing the probability of the collision with them and the impact of turbulence on the passing fish. Observations (Table 5-13) show that more fish are killed at the turbine startup because the hydraulic processes are not stabilized yet, causing the greatest shear stresses and local pressure changes of the highest intensity.

**Table 5-13 Fish mortality depending on turbine operational modes**

HPP (turbine type)	Operational mode, (% of opening of the wicket gate)	Species	Mortality, %	Reference
Foster, South Santiam river, USA (Kaplan)	80 40	<i>Oncorhynchus</i> sp.	9 21	Bell, Bruya, 1981
West Linn, Willamette River, USA (Francis)	100 90 100 90	Rainbow trout ( <i>Oncorhynchus mykiss</i> ) Chinook salmon ( <i>Oncorhynchus tshawytscha</i> )	30 – 99 20 – 100 28 – 100 19 - 100	Massey, 1967
Loch Ave, Susquehanna River, Scotland (Ossberger)	100 75 60 Startup 100 75 60 Startup	Rainbow trout ( <i>Oncorhynchus mykiss</i> )	15 – 18 21 – 25 20 – 22 56 10 – 16 28 19 52	Munro, 1968
Invergarry, Scotland (Francis)	Startup 100	<i>Salmo</i> sp.	60 18	Munro, 1966

Some publication show that various loads on the turbines cause various fish losses (Calderwood, 1945; Muir, 1959; Schoeneman et al., 1961; Lucas, 1962; Cramer, Oligher, 1964; Long, 1968; Colins, 1984; Monten, 1985; Berg, 1986; Bell, 1990). The most favorable conditions for fish downstream migration exist with the maximum HPP efficiency, i.e., when the water flow passes the turbine penstock in the most efficient way. Fig. 5.28 provides Cramer and Oligher's data (ref.: Monten, 1985) on fish losses at various efficiency rate values for Francis and Kaplan turbines. These data show that the HPP maximum efficiency rate has caused the lowest fish losses.

Mortality, %

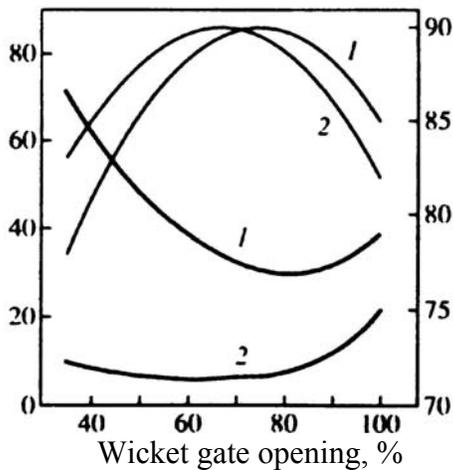


Figure 5.28 Fish losses (upper curves) and turbine efficiency (lower curves) for Francis (1) turbines and Kaplan (2) turbines (Cramer, Oligher, 1961, ref.: Monten, 1985).

The best conditions for fish passage associated with the HPP highest efficiency rate can be explained by the fact that the HPP highest efficiency rate is characterized by the minimum hydraulic losses, i.e., the wicket gate is completely open and the flow enters the turbine smoothly, with minimum turbulence, thereby minimizing the impact on the entrained fish.

Thus, fish losses from turbine passage result from various factors and depend on genus, age and size of fish. The greater HPP head value significantly aggravates the impact of other factors on the passing fish. Fish losses will vary, depending on the turbine type. They will be the smallest for bulb turbines and the greatest for Francis turbines. The operational mode of the turbine also affects the fish losses. They will be the smallest if the turbine works at the highest efficiency.

# Chapter 6 APPROACHES TO PROTECTION OF MIGRATORY FISH

This chapter is the first attempt to discuss the protection of fish migrating from the reservoirs. First and foremost, the priorities of this protection have to be established, taking into account environmental, economic and social needs. It looks like the first priority will be environmental, i.e., estimation of how the fish losses, resulting from their downstream migration, affect the fish populations. These estimates are important for the forecasting of fish development in the reservoirs to make decisions on how to provide for fish loss minimization at HPPs. Therefore, the major focus of this chapter will be environmentally oriented issues, including the following: existing methods for estimation of fish losses at HPPs, evaluations of how the fish losses at HPPs affect the fish population numbers, and strategy, principles and methods for fish protection.

It should be noted that this is the first time when these problems are being discussed, and the authors do not aim to provide all the solutions for the problems associated with minimization of fish losses at HPPs. However, we think that it is very important to describe the existing approaches to these problems, realizing that they are far from being perfect.

## 6.1 Parameters of Fish Losses at HPP Dams

There are several parameters for evaluating the fish losses resulting from their downstream migration from the reservoirs, i.e., economical, fisheries-related, and environmental. Some of those parameters have been tested at various HPPs, others require further study.

The basis for all the estimates is the absolute quantity of the fish migrants. This number identifies the scope of the downstream migration (Table 6-1). It can be obtained from the results of the yearly observations of fish downstream migration from the reservoirs.

**Table 6-1 Numbers of fish migrating from reservoirs within one year (no. x 10<sup>6</sup>)**

Species	Sheksninskoe	Ivan'kovskoe	Ozerninskoe	Volgogradskoe	Kapchagajskoe	Ust'- Khantajskoe	Al. Stambolijski	Mostiste
European perch ( <i>Perca fluviatilis</i> )	116.00	1.35	1.10	22,503	*	5.53	-	0.03
Pikeperch ( <i>Stizostedion lucioperca</i> )	6.94	0.96	0.14	33,162	274.24	-	23.50	-
Smelt ( <i>Osmerus eperlanus</i> )	33.00	1.49	0.02	-	-	-	-	-
Roach ( <i>Rutilus rutilus</i> )	0.20	0.41	0.005	600	*	*	-	0
Bleak ( <i>Alburnus alburnus</i> )	1.00	4.01	0.004	680	-	-	0	0
Carp bream ( <i>Abramis brama</i> )	0.15	5.01	0.028	657	20.14	-	-	-
Caspian anadromous shad ( <i>Alosa kessleri</i> )	-	-	-	2,978	-	-	-	-
Peled ( <i>Coregonus peled</i> )	-	-	-	-	-	2.14	-	-
Sardine cisco ( <i>Coregonus sardinella</i> )	-	-	-	-	-	3.25	-	-
Other species	1.92	1.77	0.059	12,909	68.30	0.36	0.60	0.002
TOTAL	159.21	15.00	1.356	72,867	362.68	11.28	24.10	0.032

Note. – means that the species does not inhabit this reservoir or has not been observed as a migrant; \* means that the number of the migrants is insignificant and taken into account in “Other Species” row.

The *economic* parameter provides the cost of the fish products that have been lost due to fish downstream migration. This parameter is used to estimate the fisheries losses caused by various human activities (Temporary Procedures....., 1990). To estimate this parameter, we need to know the following: the total number of the fish migrants, number of fish migrants in various age groups, the young fish survival coefficients, the average mass of an individual, and the cost per unit of fish products. This parameter is widely used in various economic calculations for the fisheries needs and we will not dwell upon it in detail.

The *fisheries* parameter is relative and it provides the percentage of the fish killed of the commercially appropriate size out of the total number of the fish caught in the reservoir. In other words, this parameter shows how much fish the fish processing industry has lost due to fish losses at the HPP. We used this parameter for the first time at Ust'-Khantajskaya HPP to estimate the fish losses there (Table 6-2.) It has been estimated that, on the average, about 50% of peled (*Coregonus peled*) and over 100% of sardine cisco (*Coregonus sardinella*) of the total fish volume caught have migrated from that reservoir.

The *environmental* parameter determines how many fish migrate of the total amount of fish in the reservoir. If the number of fish migrants is known, but there are no data on the total number of fish in the reservoir, this parameter is difficult to apply. It has been used for the first time by the author of this book (Pavlov et al., 1984) for evaluation of downstream migration from Ivan'kovskoe reservoir (Table 6-3). The most numerous migrants appeared to be the typical representatives of the pelagic zone, i.e., European smelt (24%) and pikeperch (15.2%). There were many fewer migrants from other ecological zones, i.e., Northern pike (0%), roach (0.055%), and carp bream (1.5%). The data make it possible to conclude that downstream migration can only significantly affect the populations of the first two species, i.e., European smelt and pikeperch. We have also used the environmental indicator in a slightly modified form to evaluate the downstream migration from Sheksninskoe Reservoir (Pavlov et al., 1991a). We only knew the number of adult carp bream and pikeperch there, and, consequently, we have been able to estimate the number of the young fish migrants, using the fish return coefficient (Coefficients for calculations....., 1978). Thus, 4.9% of migrants for pikeperch and 1.2% of migrants for carp bream appeared to migrate. The differences in the pikeperch downstream migration values for Ivan'kovskoe and Sheksninskoe reservoirs could probably be explained by the fact that the water exchange coefficient for Ivan'kovskoe reservoir is 15 times higher than that for Sheksninskoe reservoir. Carp bream, unlike pikeperch, are less exposed to the water intake currents, and, consequently, its downstream migration in both reservoirs is similar.

There are direct and indirect methods for quantifying the above-mentioned parameters. The direct methods imply direct calculations of the migratory fish, while indirect methods provide estimates of the fish losses, taking into account the characteristics that are not directly related to the number of migrants.

**Table 6-2 Percentage of fish migrants in Ust'-Khantajskoe Reservoir**

Species	Amount, caught, kg	Amount migrated	
		Kg	%
Peled ( <i>Coregonus peled</i> )	30,400	13,800	45.4
Sardine cisco ( <i>Coregonus sardinella</i> )	20,500	24,100	117.5

**Table 6-3 Percentage of lost (migrated) fish from the total amount of fish in Ivan'kovskoe Reservoir (1979 – 1980)**

Species	Number of fish, thousands of individuals		Percentage, %
	Residents	Migrants	
European smelt	3,220.3	773	24.0
Pikeperch	6,323	963	15.2
Bleak	88,426	3,198	3.6
Carp bream	108,776	1,586	1.5
European perch	165,553	1,346	0.81
Ide	4,769	9.5	0.20
Roach	744,030	410	0.055
Silver bream	29,151.6	3	0.01

*Note.* The data on the numbers of the fish residents have been provided by Konakov Division of National Research Institute of Fish Resources.

The diversity of the indirect methods depends on the scientific approaches to the problem and the downstream migration observation methods.

One of the indirect methods has been proposed by V.K. Konobeeva (1993 et al., 1996). This method estimates the number of potential migrants in the vicinity of the HPP water intakes with application of the downstream migration coefficient. This coefficient is a ratio between the number of the actual HPP migrants and its potential migrants. The major weaknesses of this method are that 1) it does not indicate the size of the area where the potential migrants are located; 2) the recommended frequency of fish sampling (four times a year) does not take into account seasonal variations in the number of fish in the vicinity of the HPP dam; 3) no methods for estimating the downstream migration coefficient have been provided; 4) fish entrainment in the water intake does not take into account light conditions and vertical distribution of the young fish in the area. All these weaknesses do affect the accuracy of the method application. V.K. Konobeeva used 12 daily stations at Rybinskaya, Uglichskaya and Konokovskaya HPPs and proposed to use

the following fixed downstream migration coefficient values: 0.9 for June and 0.1 in all other seasons (Konobeeva, 1996; Konobeeva, 1998). According to our observations (Pavlov et al., 1984, 1985a, б, 1991a, б, as well as Table 3.19), resulting from long-term and, in many cases, year-round observations in 45 reservoirs with a slow water exchange, the downstream migration coefficient will vary depending on the period of ontogenesis, season, and kind of species. Therefore, it is not accidental that Konobeeva has underestimated the number of migrants (Konobeeva et al., 1993; Konobeeva, 1996). In our opinion, the adequate application of this method will be less cost-effective than the direct estimations of the fish migrants.

The other indirect method is modeling. This method is not related to the estimation of the fish migrants, but implies the identification of the ecological parameter, i.e., the percentage of the fish migrants from the total number of fish in the reservoir. The environmental parameter can be estimated by means of the downstream migration model (see Section 4.5).

Therefore, the parameters described above, i.e., economic, fisheries-related and environmental, provide quantitative estimation of the fish losses at HPPs, but with (to some extent) the exception of the environmental parameter, do not allow us to evaluate the effect of those fish losses on the fish populations in the reservoir.

## 6.2 Effect of Fish Losses on Fish Populations in the Reservoirs

Regarding the status of the fish populations, downstream migration may result in the following three outcomes: 1) the population remains the same; 2) the population decreases, but then stabilizes at a lower level; 3) the population ceases to exist. The estimation of fish losses, resulting from downstream migration, makes it possible to quantitatively evaluate how migration affects the status of the fish population.

Some idea of these interrelations can be obtained by comparing the actual fish loss data with their critical values. The critical values are defined as the minimum fish loss values that will result in irreversible decrease of the fish population. Two methods are known, i.e., using the instantaneous fish losses and the percentage of the critical fish losses.

V.K. Konobeeva was the first to apply the first method on estimation of the fish losses in the reservoir (1996). The major assumption of this method is as follows:

$$M_g = M_e, \tag{6.1}$$

where:  $M_g$  is the coefficient of instantaneous fish losses in HPP, and  $M_e$  is the coefficient of natural fish losses.

If the HPP-related fish losses exceed or equal the natural fish losses during the first year of life, the HPP-related fish losses do affect the status of the fish population. But it seems absolutely inappropriate to use such an assumption due to the following reasons: 1) it does not reflect the critical fish losses that will result in the loss of the population because, even if assumption (6.1) works, some insignificant addition to the fish losses may result in the loss of the population; and 2) the natural fish losses coefficient usually includes fish losses associated with their passage through HPP. Therefore, assumption (6.1) will be true for any conditions, regardless of the actual status of the fish population, which will indicate that there is no effect of the HPP-related fish losses to the fish population in the reservoir.

Beyond that, Konobeeva verifies assumption (6.1) for each water intake separately, which, in some cases, will not give a complete picture of the actual total fish losses. For example, Ivan'kovskoe reservoir has three water intakes, i.e., Konokovskaya HPP, Ivan'kovckaya HPP and Moscow Channel. Therefore, the value of  $M_g$  should include the total fish losses for all the three water intakes.

The second method of fish loss estimation in the reservoir implies the comparison of the percentage of the lost fish with the critical fish loss percentage value. The environmental parameter described earlier (Section 6.1) can be used as the percentage of lost fish. It can be derived by direct or indirect methods. Regarding the critical fish loss, it can be estimated by the correlation between the fish loss ( $N_s$ ) and fish replenishment ( $J$ ) values. It seems that, if  $N_s > J$ , the fish population will decrease. Therefore, the critical status of the population should be equal to the following:

$$N_s = J. \quad (6.2)$$

The decrease of the adult fishes of a certain species in the reservoir will be as follows:

$$N_s = N_p + N_l + N_m + N_e + N_a, \quad (6.3)$$

where:  $N_p$  is the number of fish in the commercial catch;  $N_l$  is the number of fish in the amateur catch;  $N_m$  is the natural fish loss;  $N_e$  is the number of the HPP-migrated adult fish; and  $N_a$  is the number of adult fish lost due to other factors.

The population ( $J$ ) will increase as follows (without taking into account the fish newly arriving from the HPP tailwaters):

$$J = J_u - J_m - J_e - J_a, \quad (6.4)$$

where:  $J_u$  is the natural replenishment of the population;  $J_m$  is the number of the young fish lost due to natural death;  $J_e$  is the number of HPP-migrated young fish; and  $J_a$  is the number of young fish lost due to other factors.

In accordance with (6.2), we'll obtain the following:

$$N_p + N_l + N_m + N_e + N_a = J_u \cdot J_e \cdot J_a \cdot J_m \quad (6.5)$$

Then the critical value of the fish migrated from the reservoir will be as follows:

$$J_e + N_e = J_u - N_p - N_l - N_m - N_a - J_m - J_a \quad (6.6)$$

Dividing the left and the right parts of (6.6) by the total number of fish in the reservoir ( $N_0$ ), we'll obtain the following equation:

$$D_k = \frac{J_u - N_p - N_l - N_m - N_a - J_m - J_a}{N_0} \quad (6.7)$$

The comparison of the critical downstream migration related fish loss ( $D_k$ ) with the ecological parameter ( $D_e$ ) gives an idea on how the fish losses affect the status of the fish population. Specifically, if  $D_e > D_k$ , the population will go down.

This method seems to be difficult to use because the components of (6.7) are not very straightforward to estimate because there are no direct linear relationships between them and various abiotic and biotic factors. However, the theory on dynamics of fish populations might be helpful for these needs. Some simulation models have already been developed within this theory to take into account the effect of various factors, including downstream migration, on the number of the fish populations (Kriksunov, Polonsky, 1991; Vekilov et al., 1995). The models imply conventional methods for evaluation of fish population growth due to natural replenishment and their losses resulting from factors of various nature.

Such models make it possible to control the number of fish in the reservoir and estimate the critical value of the fish losses, which is important for providing timely and accurate evaluation of the effect of downstream migration on the fish population.

Thus, only data on the dynamics of the fish population can provide accurate information on how the downstream migration affects fish populations in the reservoirs. Several methods for estimation of fish losses can be used, and one of the major methods is to model the number of fish in the reservoir, which is important for both identification of the critical fish loss values and for control over the fish populations in the reservoir. Further development of the fish downstream migration models, specifically, more detailed study of the model parameters, are required to be able to provide timely and accurate evaluation of the status of the ichthyofauna in the reservoirs.

### 6.3 Strategies for Fish Protection at HPP Dams

The strategies for fish protection at HPP dams depend on the scale of migration, i.e., sizes of the migration rings. Some species perform very long spawning and downstream

migrations and, in the further narration, we'll define them as migrants. These are, first of all, diadromous and amphidromous fishes, as well as those resident fishes that perform migrations within the river basin. Other fishes (resident fishes) perform short migrations within the same reservoir or river and its tributaries. Since there are two different scopes of fish migrations, there should be two different fish protection strategies, i.e., for migrants and for resident fishes.

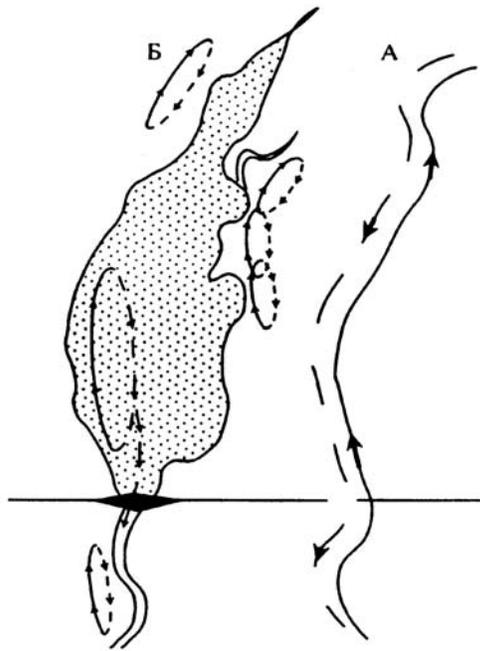
*Strategy for Protection of Fish Migrants.* To preserve the populations of the fish migrants, the conditions for their reproduction should be provided. They perform long spawning migrations back and forth from spawning areas, and HPP dams are often an insurmountable barrier for them. Therefore, it is necessary from the economic and environmental standpoints that the spawning areas be preserved and both upstream (spawning) migrants and downstream migrants pass through the dam safely in order to maintain their migration cycles (Fig. 6.1).

When the HPP dams were built in the rivers, the major focus was given to the passage of the spawning migrants up the river. Special fish passage facilities have been designed for that. But another problem, i.e., downstream migration of the young fish, had been given little attention. And, even if the spawning is successful, the fish population will not be replenished because most of the young fishes will be lost during their downstream migration through the HPPs, going back from the spawning locations to the feeding places.

Very little has been done in Russia to protect downstream migrants. More has been done in other countries lately in this respect, but, even there, this problem still presents a lot of challenges. There are two major approaches to protect the downstream migrants, i.e., 1) modify the turbine designs and operational modes to assure fish safe passage through the HPPs; and 2) design special collectors and tubes for the fish to bypass HPPs.

The first approach has not been very well developed yet because any efforts in modifications of the HPP turbine design will involve certain energy losses. However, the foreign publications do discuss optimization of turbines for providing fish safe passage through the HPPs (Davies, 1988; Cada, 1990; Bell, 1991; Cada et al., 1997).

Regarding the second approach, screens have been used, as well as “curtains” of air bubbles, and various light, electrical, and sound signals. (This approach will be described in more detail in other sections of this chapter).



**Figure 6.1 Migration Rings for Fish Migrants (A) and Resident Fish (B)**

*Strategy for Protection of Resident Fish.* Short migrations of resident fish do not interfere with the migration rings (see Fig. 6.1). The populations of the resident fishes may decline due to their downstream migration from the reservoir. However, the role of downstream migration for resident fishes depends on whether they inhabit lakes or manmade reservoirs. In lakes where fish can freely go both upstream and downstream, their migration sustains or increases the population due to expansion of the young fish habitat within the reservoir. In manmade reservoirs, downstream migration is imminent unless there are facilities for returning the fish from tailwaters back to headwaters, but very few HPPs have such facilities. Therefore, downstream migration from manmade reservoirs causes irreversible fish losses to the reservoirs.

Thus, the protection of resident fishes in the reservoir should aim to preclude their migration from the reservoir. To implement this strategy, fish entrainment into the HPP facilities has to be prevented.

The conclusion is that the strategies for protection of fish migrants and residents are entirely different. Safe passage through the HPP has to be provided for the fish migrants, while any downstream migration from the reservoir should be prevented for the resident fish.

## 6.4 Principles of Fish Protection

To prevent fish entrainment in the HPP facilities, control over fish movement needs to be provided, and the fish is considered to be as follows:

a system of living organisms with a certain spatial-temporal distribution structure;  
living organisms that react to various stimuli;  
physical objects that have a certain size, density and other physical properties.

These assumptions have made it possible to identify three principles of fish protection from entrainment in the HPP water intake (Pavlov, Pakhorukov, 1973).

*Ecological principle*, i.e., application of patterns related to fish life cycle (distribution and migrations) and the reasons for their entrainment in the water intake.

*Behavioral principle*, i.e., application of behavioral reactions of fish towards various stimuli (light, sound, electric, hydraulic, or pressure-induced, etc.)

*Physical principle*, i.e., application of physical phenomena to prevent the fish entrainment (mechanical barriers, difference between the water density and fish body density, etc.)

These principles define the concept of fish protection. Next, we distinguish the methods of fish protection that are based on one or several principles. Then we identify the measures and devices to use for implementation of the methods of fish protection.

Incorrect interpretation or applications of the above-mentioned categories have caused a lot of confusion in methodology and terminology. No serious attention has been given to the principles of fish protection, and, for a long time, an empirical approach has been the major approach in fish protection issues.

The principles of fish protection can be used for protection of both fish migrants and resident fish. In the first case, the principles are aimed at providing a safe passage to the HPP tailwaters. In the second case, the fish entrainment to the HPP water intake should be prevented and the fish need to be transferred to the safe area of the reservoir.

## 6.5 Methods of Fish Protection

Many varied devices and tools have been described in literature for preventing fish entrainment and loss in the HPP water intakes: Pavlov, Pakhorukov (1983); Malevanchik, Nikonorov (1984); Manual on Design....., 1988; Pavlov (1989); Ripinsky (1991); Petrashkevich (1992); Clay (1995). There is no need to repeat what has already been described. We'll only discuss those methods that we consider the most effective for HPP applications.

### **Ecological Methods of Fish Protection**

Ecological methods of fish protection look very promising, but they have not been widely applied yet because, in some cases, they may require redesign of the water intake. These methods do not imply applications of certain devices, they rather imply implementation of the wide range of fish protection activities, such as appropriate locations of water

intakes and adjustment of time for water intake. These measures could reduce the fish losses by a factor of a few hundred. Therefore, we consider them very important, especially for the early young resident fish, the downstream loss of which is the most common. These measures can also be used for the protection of fish migrants. However, it should be noted that most environmental methods for fish protection are associated with adjustment of the water withdrawals in time and in space, which may be difficult to implement at some HPPs with well-defined and strictly enforced water intake and water consumption modes.

*Adjustment of Water Intake in the Entire Reservoir.* This method is based on the characteristics of young fish distribution in the reservoir (the locations for spawning, feeding, hibernation and migration rings). The water intakes are proposed to be installed outside the spawning areas because it is in the spawning areas where, for a short time, the highest concentrations of eggs and young fish are observed. It is also important to minimize water withdrawals along the young fish migration routes.

*Zone-Related Water Intake Adjustment.* It is important that water intake be installed correctly in regards to the ecological zones of the reservoir. Specifically, the littoral and the pelagic zones of the reservoir differ much regarding their species specific structures, size, age, and quantity of fish. All these factors need to be taken into account in the following way.

1. Minimization of water intake from littoral zone. Installation of water intakes in the littoral zone needs to be avoided because most of the young fishes inhabit warmer and food-rich waters there.
2. Alternating water intake from different ecological zones due to seasonal changes in the fish concentrations.
3. Creation and expansion of the existing biotopes for the accumulation of fish in areas away from the water intake. This method can be successfully implemented for protection of resident fish. It implies fish protection measures for the entire reservoir, specifically: creation of bays and coves with the complete set of ecological zones, and expansion of the littoral zone in the reservoir for providing favorable conditions for the young fish development.

*Vertical Adjustment of Water Intake.* Since many species have well-defined vertical distribution, it can be used for their protection from water intake entrainment. It implies the following.

1. Installation of water intake in the depth with the minimum concentration of young fish. It is known (Bell, 1991) that young Salmonidae species do not go below 30 meters deep. Therefore, if the water intake is located below 30 meters, their entrainment in the water intake will be avoided. At Nurekskaya HPP, the water intake is located 50 meters deep, and there is no fish entrainment there (Pavlov et al., 1992).
2. Alternating the depth of water intake to avoid the vertical distribution of young fish, depending on the season. This method can be applied for the protection of resident fish at HPPs, i.e., providing water intake from the depths with the minimum fish concentrations.

3. Installation of logging booms or other shielding devices in front of the water intakes to preclude intake of surface water. However, this method may not be effective for fish migrating in deep waters. This method is widely applied in other countries for providing a bypass for the fish migrants (Bell, 1991; Clay, 1995; Cada et al., 1997).

*Daily Adjustment of Water Intake.* This method takes into account daily dynamics of young fish entrainment in the water intake. It is considered to be one of the most important and, probably, the most universal (regarding its application with various species) method for fish protection. This method means that water intake in the evening and at night needs to be minimized. However, since peak load hours for some HPPs are in the evening or early morning, this method is probably difficult to apply at HPPs.

*Seasonal Adjustment of Water Intake* is related to significant seasonal changes in the fish concentrations in the individual parts of the reservoir. It is especially relevant for diadromous and amphidromous fishes. Knowing the specific periods of their migrations, the HPP water intake can be restricted. It is implemented at Nizhne-Tulomskaya HPP for providing safe passage of salmon\* smolts.

Thus, the ecological methods for fish protection can be potentially very promising if the regularities and mechanisms of fish downstream migration are taken into account. It is especially important to take into account vertical and zone-related water intake adjustments. Many of these methods can be used for fish protection at HPPs. However, there may be some limitations there, associated with seasonal and daily modes of water intakes.

### **Physical Methods of Fish Protection**

Physical methods of fish protection should be considered one of the first solutions to this problem. It implies treating fish as a physical object. Physical methods are typically associated with installation of various screens and other mechanical barriers or filters in front of the water intake, which preclude the fish from entrainment in the penstock, but preserves their life. Thus, such characteristics of screening are important as the screening velocities, duration of fish contact with the screening material, the structure of this material, as well as size and strength of their skin and tissues.

Impingement is followed by removing the fish from the screening material, which is entirely different from the situation when the fish leaves the screens independently (behavioral method of protection).

To remove the fish from the screens, water jets are used. In some foreign countries, mobile screens are used (Bates, 1960, 1970) or special trenches for fish collection (Sommers, 1980). However, the screens appear to be ineffective for HPP conditions and their maintenance (cleaning) is very expensive (Bell, 1991).

In our opinion, screening as a method for fish protection at HPP has very limited capabilities. Screening alone can only be used for trapping large fish, i.e., over 50 mm

long. To protect young fish, screening should be used in addition to other various fish protection devices based on behavioral methods of fish protection.

### **Behavioral Methods of Fish Protection**

Behavioral methods of fish protection are based on application of fish behavioral reactions resulting from activation of certain receptors, i.e., vision, hearing, tactile, or pressure sensors. Primarily, the stimuli that cause fright followed by exit from the water intake zone are used. Beyond that, stimuli may lead the fish away from the water intake zone, or restore their orientation in the water flow. The latter is especially important for passive migrants. Behavior-based devices for fish protection are based on the following seven methods: light, electric, hydraulic, tactile-hydraulic (two methods), sound and hydrostatic methods. At HPPs, these devices have to be installed in the reaction zone, i.e., outside the zone of critical velocities. Behavioral methods are very widely used at water intakes of various performance and most of them can be successfully used at HPPs for protection of both migrants and resident fish.

*Light methods.* Some fish are known to be attracted to light, other fish are indifferent to it, or try to avoid it. The fish reaction to light depends on a number of biotic and abiotic factors and, therefore, even reactions to light within a species may vary, depending on the period of ontogenesis. Most young fish use light for orientation in the water flow. Thus, light may either scare or attract fish, as well as improve their orientation capabilities. However, light methods of fish protection have not been widely used yet either in Russia or other countries (Bell, 1991).

*Electrical method* is based on the fact that fish avoid electrical fields. However, the electrical barriers installed at a number of HPPs have proved to be ineffective for young fish less than 50 mm long. Some foreign authors (Clay, 1961; Vibert, 1967) indicate that this method is inappropriate for protection of early juvenile fish.

It should be noted that some electric field intensities may suppress fish rheotaxis, thereby causing their drifting with the current. Therefore, at high current velocities, the fish may fail to avoid the water intake zone unless some additional special methods for removing the fish are used. It seems to be the most effective if the electrodes are located at an angle to the fish removal flow.

We do not have data on how effective this method is at HPPs, but we believe that, if applied properly, it can be used quite successfully.

*Hydraulic method* can be used for two purposes, i.e., for redistribution of young resident fish performing downstream migrations and for relocation of migrants. Redistribution of resident fish performing downstream migration can be initiated by the currents and behavioral reactions of the young fish (Pavlov, Shtaff, 1981). To relocate the migrants, special currents and turbulence need to be generated to either attract or scare away the fish (Pavlov, Turukov, 1986, 1988; Skorobogatov et al., 1996; Pavlov, Lupandin, 1998).

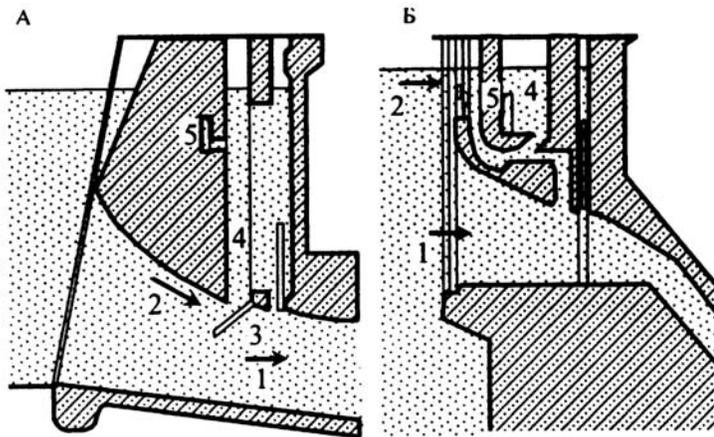
*Tactile-hydraulic method with application of passable barriers* is widely used and have many variations. The major principle here is to apply a number of similar stimuli, mostly hydraulic, tactile and optical. The difference will be only the number of such stimuli. The major goal of the barriers is to affect the hydraulic structure of the flow.

The following permeable barriers are common: louver type screens (Bates, Vinsonhaler, 1954), suspended chains (Brett et al., 1958), air bubbles, screens, water jets, and various plates, including L-shaped plates. The behavior of fish in front of these barriers is affected by visual, tactile and hydraulic stimuli. The application of the flow excitation for controlling the fish movement makes it possible to consider the hydraulic method of preventing the fish from entering the water intake quite feasible. The latest results on the application of this method look very promising.

*Tactile-hydraulic method with applications of impassable barriers* also have a lot of variations. The fact that the barrier is impermeable gives a lot of possibilities for controlling the fish behavior because the fish cannot enter the water intake. However, the powerful hydraulic and tactile stimuli generated there make the fish resist their compression by the barrier and it may badly affect their swimming capabilities. Unlike impassable barriers, passable barriers are based on behavioral reactions and also physical methods of fish protection.

*Sound method.* Fish are known (Protasov, 1978; Balashkand et al., 1980) to react to acoustic stimuli. However, application of sound for fish protection has not been very common, probably due to the frequency spectrum of the applied sound fields. It has been proved experimentally (Pavlov, Sablin-Yavorsky, 1991) that low frequency sounds scare the young fish away. We consider this method potentially very effective.

*Hydrostatic method* is based on the compensating motion reaction of fish, resulting from a change of the hydrostatic pressure. This method is widely used abroad for protection of young Salmonidae species during their downstream migration. The smolts are known to migrate in the upper levels of water and then descend into the HPP water intake (Thorpe et al., 1981; Thorpe, 1982; Cada et al., 1997). As the observations show, those fish tend to go close to the upper edge of the penstock (Cloey, Barila, 1988). Such behavior has been used for the collection and safe transportation of the migrants to the tailwaters (Fig. 6.2, A). Currently, a few systems of that kind have been implemented in the US. They save about 85% of Salmonidae individuals (Smith, Farr, 1975; Arnold, 1978). However, there are some data on the negative effect of these systems (Ferguson, 1992). The *Hydroproekt* Russian Research Institute has designed and developed similar systems for protection of resident fish (Fig. 6.2, B). The only difference is that it has a special channel for pumping out the surface waters with high concentrations of young fish into the fish collector.



**Figure 6.2 Hydrostatic Systems for Fish Protection at HPPs.**

A – ref.: Arnold, 1978; Б – *Hydroproekt* design;

1 – water flowing to the HPP turbine; 2 – water rich in fish; 3 – channel for removing the fish from the water flowing into the turbine; 4 – fish collector; 5 – fish release from HPP

Reliability and effectiveness of fish protection systems depend on their ability to remove the fish from the water intake zone. The decision on which particular system or method to use depends on the specific HPP design. But in all cases, a transit fish removal flow has to be generated, and the velocity of this transit flow has to exceed the critical current velocity for the fish to be protected. For removing the migrants, usually the difference in water depths in the dam is used. The fish is transferred to the tailwaters by special tubes or channels (Clay, 1995). If there are no special tubes or channels available, the fish protection systems need to be supplied with them. To generate a current in the fish removal tubes, various hydraulic accelerators could be used, but, in all cases, such transportation should be safe for the fish (Pavlov, Pakhorukov, 1983; Malevanchik, Nikonorov, 1984).

Thus, two major groups of fish protection methods can be discerned, i.e., environmental methods and behavioral methods. Physical methods can only complement those two. Many fish protection systems based on these methods can be successfully applied at HPPs and many of them have already been successfully tested. The most promising for resident fish appear to be environmental methods. However, behavioral methods are more common. They make it possible to preclude fish entrainment in the HPP water intake and control the fish movement. These methods are based on two major conditions, i.e., control over fish behavior by applying various stimuli and removal of the fish from the water intake zone. These methods can be successfully used for protection of both migrants and resident fish.

# CONCLUSION

This publication identifies and quantifies major factors and mechanisms of downstream migration of fish from HPP reservoirs, thereby adding to the theory of fish migration in fresh water, specifically, in reservoirs with a slow water exchange.

Mechanisms of downstream migration have several levels. The mechanisms of the first level generate the precursors of the downstream migration, the mechanisms of the second level implement downstream migration and the mechanisms of the third level determine spatial and temporal structure of the distribution of migrants. The studies on downstream migration show that its major biological mechanisms will be the same for limnic and lotic types of reservoirs. However, the conditions for downstream migration in reservoirs and lakes will differ from those in rivers due to differences in water intakes and formation of currents. Besides, different conditions for fish migration will be generated in different areas of the reservoir. Therefore, in reservoirs, the downstream migration process consists of two phases, i.e., fish entrainment into the water intake zone and fish movement through the water intake zone, resulting in their migration to the HPP tailwaters.

In most HPP reservoirs, fish are taken to the water intake zone by the currents. It happens if the fish inhabits or temporarily stays in the pelagic zone of the reservoir, which is made possible by the mechanisms of the *first* level.

When the eggs are hatched and the larvae leave the spawning places, the pelagic distribution of larval fish will depend on the morphological adaptations and non-specific inherent behavioral reactions. The migration of fish in the littoral zone is also made possible only if some of the littoral species go to the pelagic zone. However, taking into account the fact that those species that leave the littoral zone for the pelagic zone are older than the migrants in the rivers, we think that the key role in their migrations to the pelagic zone belongs to non-specific behavioral reactions. There are some grounds to believe that not only in rivers (discussed earlier), but also in reservoirs with a slow water exchange, migration of larval fish and fry from the littoral to the pelagic zone may be associated with a special, so-called migration “mood.” It is characterized by a high hormonal status of the migrants and their specific behavioral reactions. Earlier, such migration “mood” has been described for diadromous juvenile fish, but the latter migrates at a much older age.

The mechanisms of the *second* level in reservoirs with a slow water exchange and in rivers are connected with the methods for rheotaxis “neutralization”. Such neutralization occurs if the current velocity exceeds the critical velocity for fish, or there are no conditions for fish orientation. In the reservoirs, immobile markers are located far away from the pelagic zone, thereby making it impossible for orientation not only at night, but also in the daytime. Hence, the fish migrate passively in those reservoirs all the time.

The mechanisms of the *third* level operate in reservoirs and rivers in entirely different ways. The migratory fish distribution in the reservoirs with a slow water exchange

depends on the water intake currents, wind currents, and compensating currents, as well as the vertical daily movements of fish. All these currents are capable of changing both velocity and direction of the fish migration. Therefore, in reservoirs and lakes, the mechanisms of the third level can accelerate, slow down or even prevent downstream migration, while, in rivers, downstream migration does not depend on these mechanisms.

Since the system of currents has a constant component, i.e., water intake current, some fish from the pelagic zone are bound to enter the water intake zone. The water intake zone, or the water intake influence zone, is defined as the area of the reservoir adjacent to the dam where the current velocity differs from the average current velocity in the reservoir, with its value increasing from its upper border downstream. Due to a faster velocity, deviation of the velocity vector from the horizontal line, and closer immobile markers, the information media there is much better than in the open part of the pelagic zone. Thus, the conditions for fish orientation improve, thereby preventing their entrainment in the water intake.

There are two more zones in the water intake zone, i.e., reaction zone and zone of critical velocities. The fish behavior will be different in those zones. The reaction zone is the zone where the fish may resist their drifting with the current, i.e., they have rheotaxis and other reactions to maintain their location at a certain depth level (hydrostatic reaction and photoreaction). As a result, downstream migration for even very young fish may be prevented. The zone of critical velocities is adjacent to the gatewell and it is located inside the reaction zone. The flow velocity there is higher than the critical current velocity for fish and, consequently, all fish drift toward the gatewell.

In the water intake zone, the fish migrants are exposed to changes in many abiotic factors of the environment, such as current, light, water temperature, and hydrostatic pressure. These factors may significantly affect behavioral reactions of the fish.

The quantitative approach to the studies of regularities and mechanisms of downstream migration has made it possible to develop a model of downstream migration. The output parameter of this model is the percentage of the migrants taken from the total number of fish in the reservoir. Some further studies in this respect require evaluation of the behavior of the fish migrants as a function of various environmental factors typical for the water intake zone, as well as clarification of time and scope of the fish migration from the littoral zone to the pelagic zone.

The overall review of the downstream migration studies for reservoirs and lakes has made it possible to identify the key factor in downstream migration of resident fish from reservoirs with a slow water exchange. This factor is associated with ecological zones of water intake that quantitatively affect the influence of the water intake current on individual ecological zones of the reservoir. The ecological zones of water intake imply many correlated environmental characteristics that significantly affect the fish downstream migration from reservoirs with a slow water exchange. The ecological zones of water intake affect such characteristics of the fish downstream migration as species specific structure of the migrants, their age, seasonal and partially daily dynamics of the

downstream migration, and migration index that shows the percentage of migrants taken from the total number of the fish in the reservoir, as well as the correlation between the active and passive types of downstream migration. The ecological zones of water intake allow us to predict reliably the downstream migration parameters for the young fish.

The data obtained appear to be helpful in evaluating the role of the downstream migration in the development of the fish resources. Unlike lakes, downstream migration can be harmful for the fish populations in the reservoirs. To provide accurate estimates, theory on dynamics of fish populations has to be used.

Apart from theoretical issues, a number of practical issues have been described in the book. The final phase of downstream migration is the fish passage through the turbines, frequently resulting in fish injuries and losses due to pressure changes, cavitation, turbulence and contact with the runner blades. The degree and probability of injuries and losses depend on the fish size and age, as well as on the HPP head value, turbine design and operational parameters. Francis turbines and a higher hydraulic head seem to cause more injuries. Bulb turbines and operation with the highest efficiency reduce the fish losses. The literature review has identified some ways to minimize fish losses.

Two strategies for fish protection at HPP dams can be proposed, i.e., strategy for protection of migratory fish and strategy for protection of resident fish. For the migratory fish, their safe passage through the turbine has to be provided, while for the resident fish, their migration from the reservoir needs to be prevented. Two major groups of methods for fish protection have been identified, i.e., environmental and behavioral methods. Some of the fish protection systems based on these methods have already been tested and demonstrated at some HPPs.